The Ocean's Weather: Understanding The Temporal Variability of Mesoscale Eddies

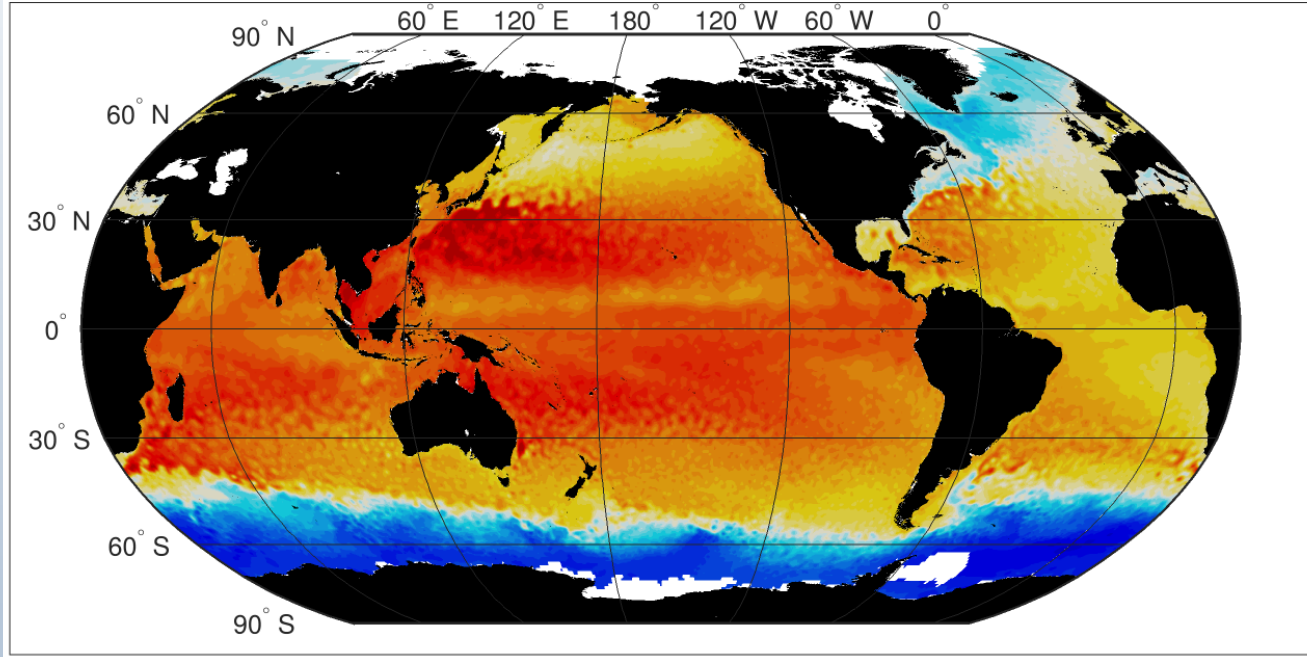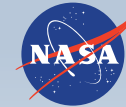Andrew Delman (JPL/Caltech), Tong Lee (JPL/Caltech), Bo Qiu (University of Hawaiʻi, Mānoa)

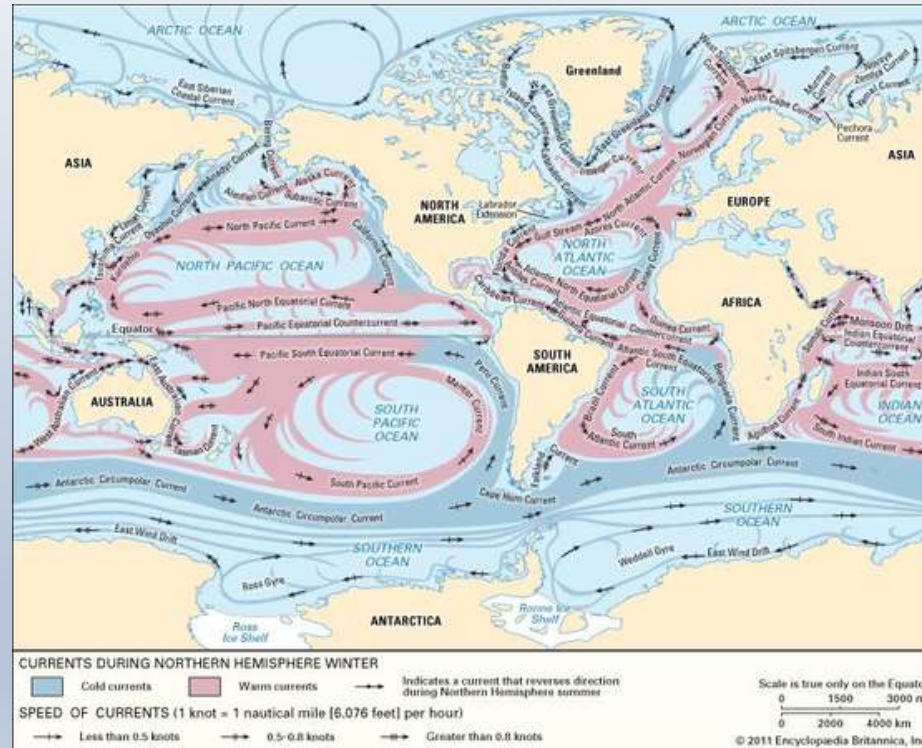Image: Absolute dynamic topography on 1998 Jan 01, from SSALTO/DUACS

Jet Propulsion Laboratory
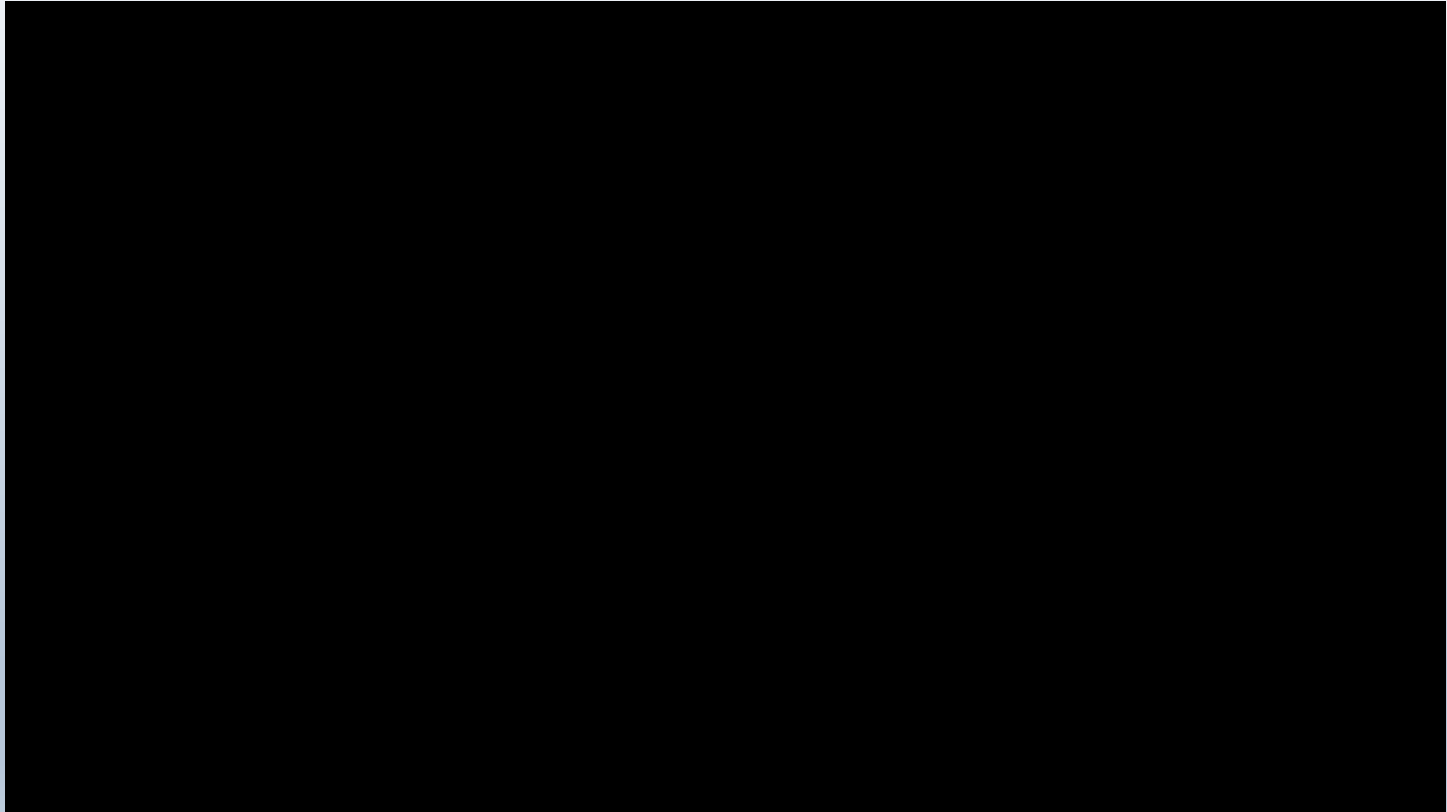California Institute of Technology

California Institute of Technology

17 May 2019

A "traditional" view of the ocean circulation
(through most of the 20th century)

Source: Encyclopædia Britannica

## Then came Seasat, Geosat, and in 1992, TOPEX/POSEIDON…

Source: NASA JPL PO.DAAC YouTube channel, available to public (https://www.youtube.com/watch?v=F8zYKb2GoR4)

Impact of eddies on the ocean and the climate system

- Transfer of ocean energy between large and small scales
- Biogeochemical impacts
- Transport of heat/salt across strong oceanic fronts, and between low and high latitudes
- Impacts on atmospheric dynamics
- Parallels to atmospheric dynamics

Rough schematic energy budget of the global ocean

Wunsch and Ferrari (2004)
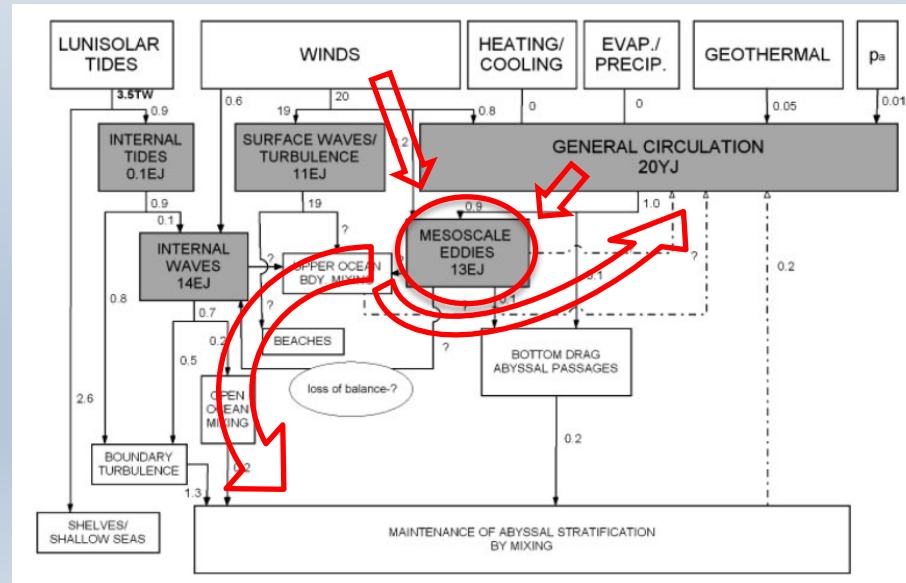
Large-scale (1000s of km)

Mesoscale/submesoscale (1-100s of km)

Small-scale (meters to mm)

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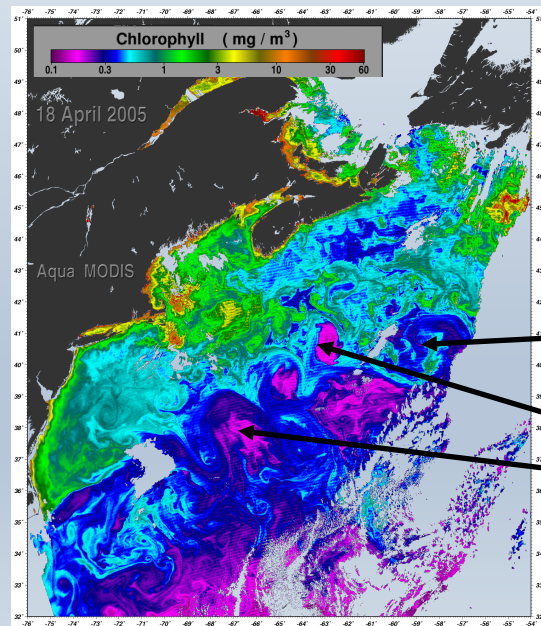
Surface chlorophyll concentrations
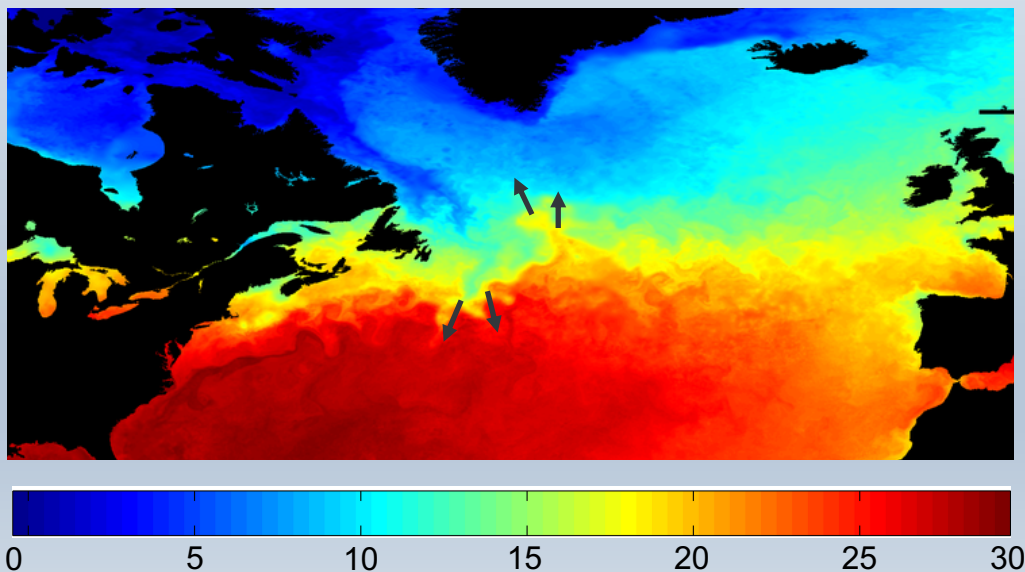from Aqua MODIS, 18 April 2005

Cyclone

Anticyclones

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JPL MUR sea surface temperature,
4 September 2018

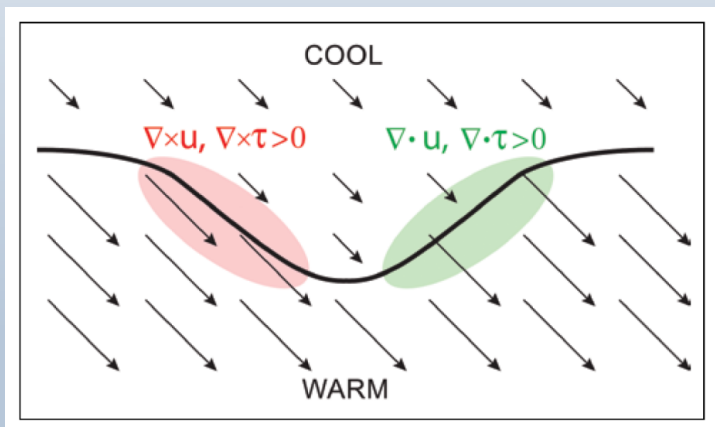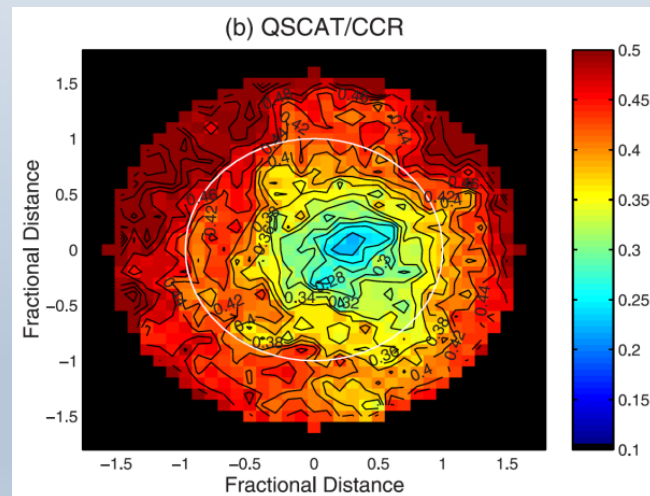# Impact of eddies on the ocean and the climate system

- Transfer of ocean energy between large and small scales
- Biogeochemical impacts
- Transport of heat/salt across strong oceanic fronts, and between low and high latitudes
- Impacts on atmospheric dynamics
- Parallels to atmospheric dynamics

Schematic – adjustment of surface winds over SST fronts
Chelton and Xie (2010)

Composite cloudiness over cold-core rings, from satellite SST images
Park et al. (2006)

Impact of eddies on the ocean and the climate system

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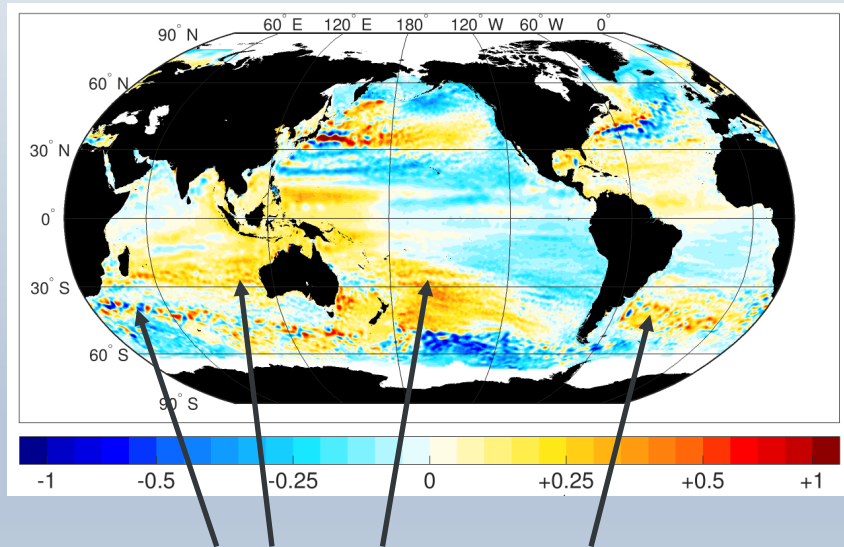- Impacts on atmospheric dynamics
- Parallels to atmospheric dynamics
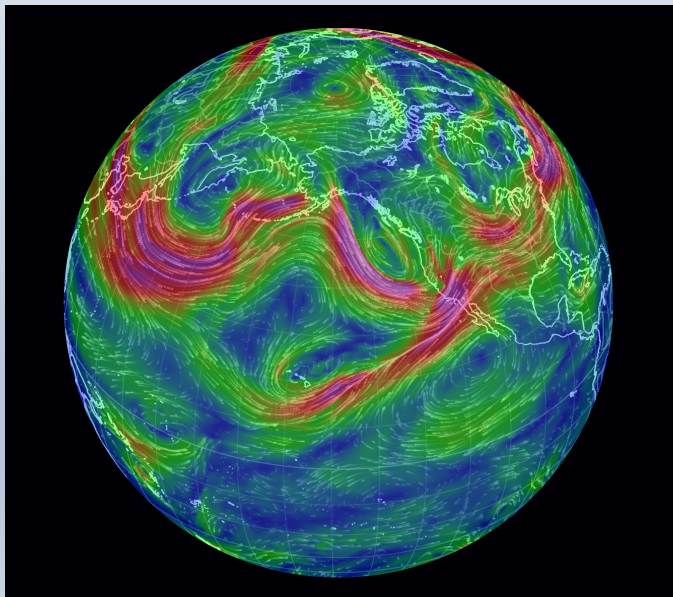
500 hPa **atmospheric** winds, 14 Feb 2019
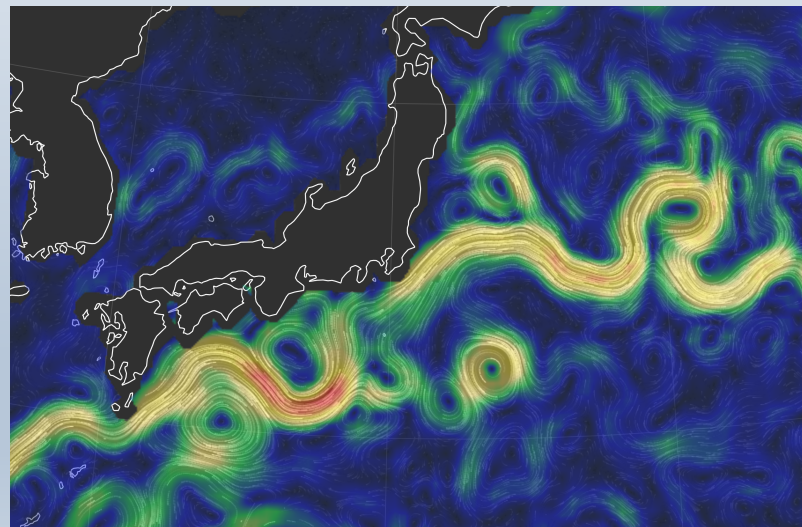
Surface **ocean** currents near Japan, 10 Feb 2019

One more possible impact: the oceanic mesoscale may influence regional rates of sea level change

Sea level trend minus global mean (cm yr^{-1}), 1993-2016

Difference in sea level trend (1992-2013) forced by wind stress & eddy momentum fluxes, vs. wind stress alone (Qiu et al. 2015)

Note the presence of numerous mesoscale features, that are often arranged in zonal bands
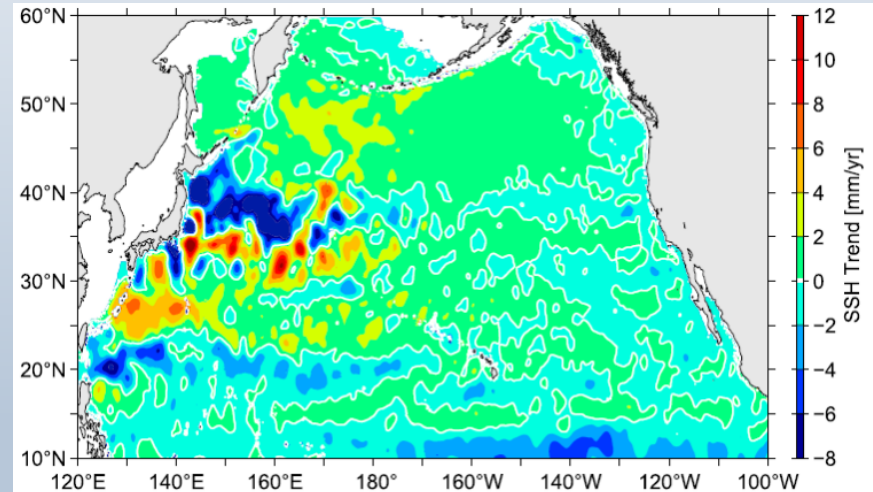
Research focus

- **Part 1: Where are changes in eddy kinetic energy (EKE) on interannual and decadal timescales associated with changes in local sea surface height (SSH)?**
    - Do local changes in SSH (and SSH gradients) influence eddy activity
    - Does eddy activity influence sea level (SSH) variability?
    - Or are SSH and EKE variability forced by common mechanism(s)?

- **Part 2: What other characteristics of the ocean contribute to interannual and decadal EKE variability?**

    - In a regional study, we considered the role of temporal variations in subsurface density and potential vorticity gradients.

A measure of eddy strength

Eddy kinetic energy (EKE)

$$EKE = 0.5*[(u')^2 + (v')^2]$$

- u' and v' are the components of the velocity vector, with the time-mean velocity removed

- Surface EKE is a useful diagnostic, because it can be computed from sea surface height (SSH) using the geostrophic relationship (pressure/height gradients → velocities)

Time-mean EKE, from gridded altimetry data (SSALTO/DUACS)
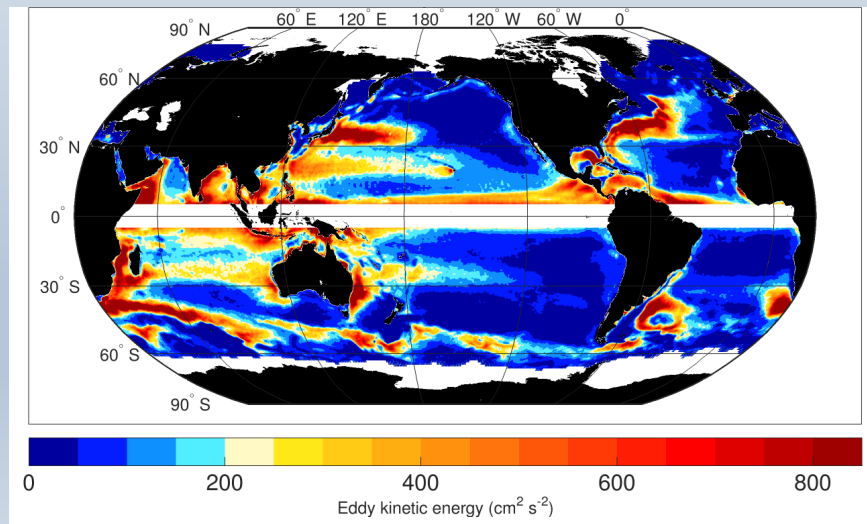
Sea level and EKE co-variations

Local correlation of SSH and EKE, at interannual/decadal timescales
(only correlations of >95% significance are shaded)
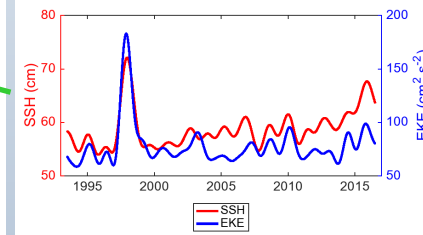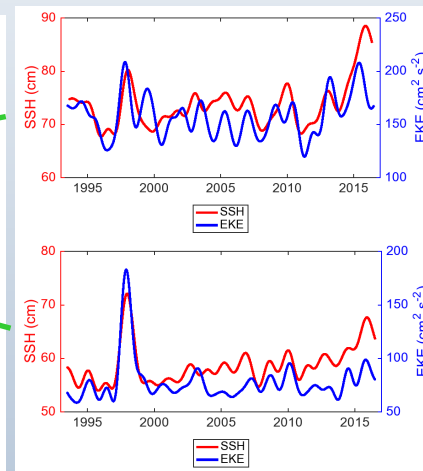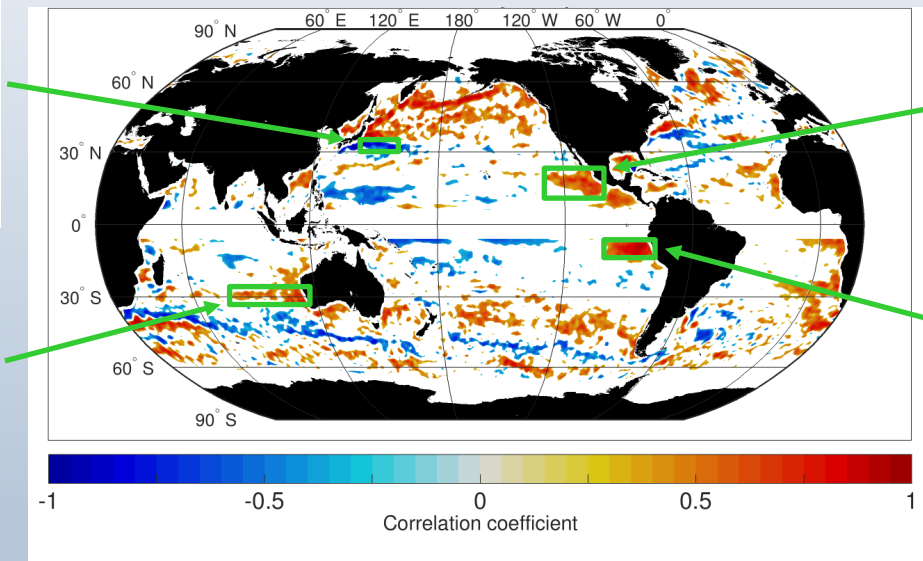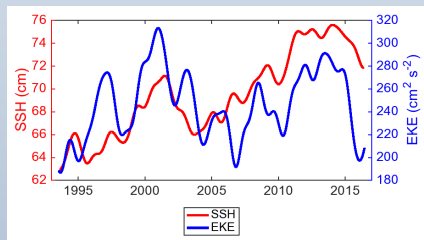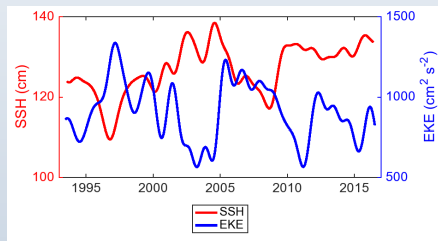
- Change in sign of SSH-EKE correlation occurs across many strong currents

Sea level and EKE co-variations

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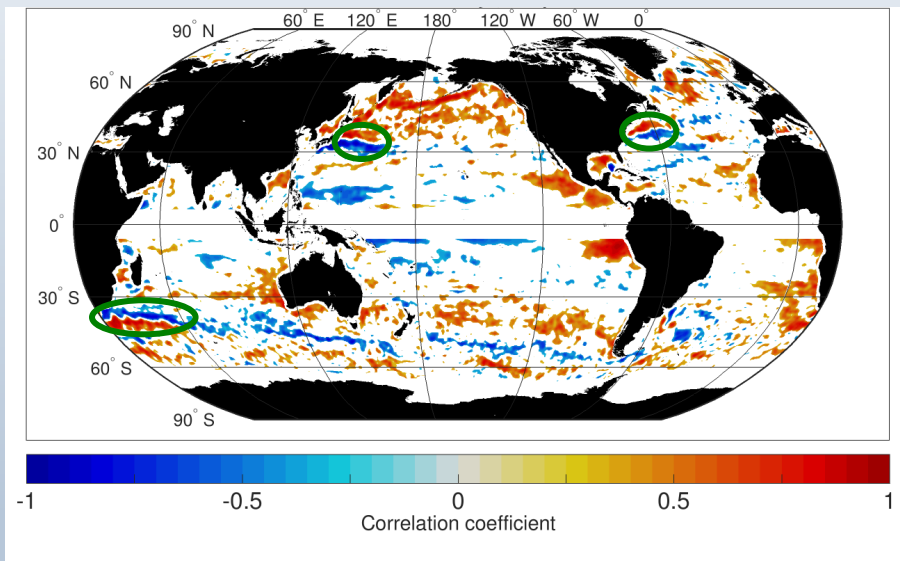
Time mean of SSH
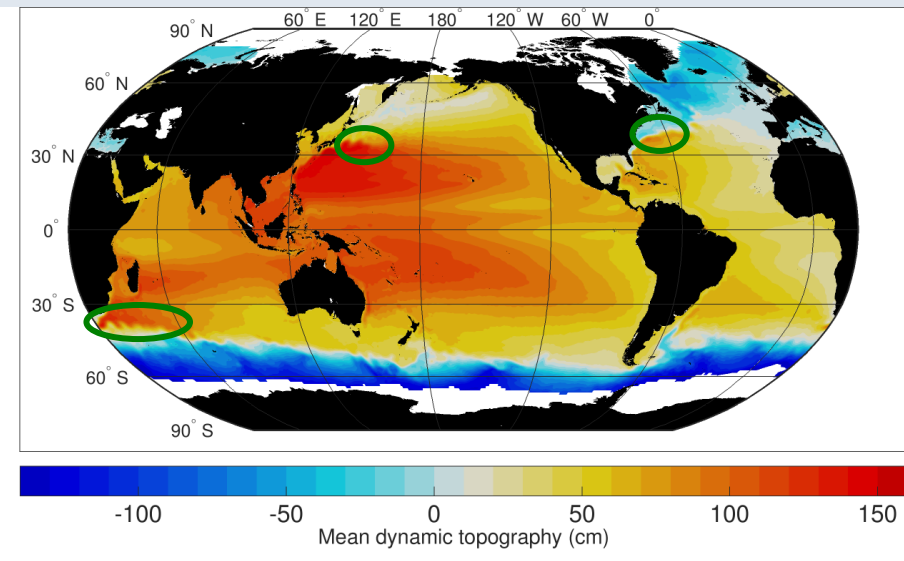
- Change in sign of SSH-EKE correlation occurs across many strong currents
- Notably, the SSH-EKE correlation near strong currents suggest that **EKE is higher when the cross-jet SSH gradient is weaker**
  → Strengthening of cross-frontal SSH gradients is **not** associated with increased eddy activity

EKE impact on sea level variability due to anticyclonic/cyclonic bias?

- We consider the relative contribution of anticyclonic vs. cyclonic mesoscale phenomena to EKE, as follows:
  - Low-pass spatial filter SSH in two dimensions, with the cutoff wavelength varying by latitude
  - The residual is the **mesoscale SSH or SSH$_{meso}$**
  - SSH$_{meso}$ > 0: anticyclonic eddies (and other mesoscale phenomena)
  - SSH$_{meso}$ < 0: cyclonic eddies/other mesoscale phenomena

Snapshots of SSH components on 1998 Jan 01
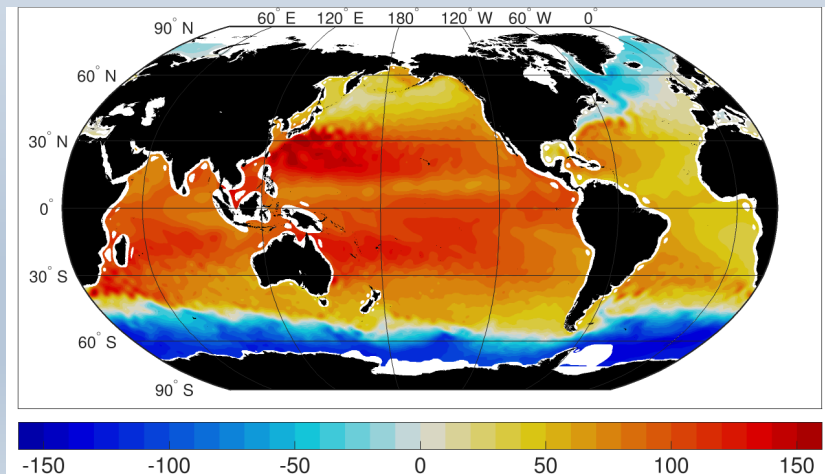
Low-passed SSH$_{lp}$ (cm)
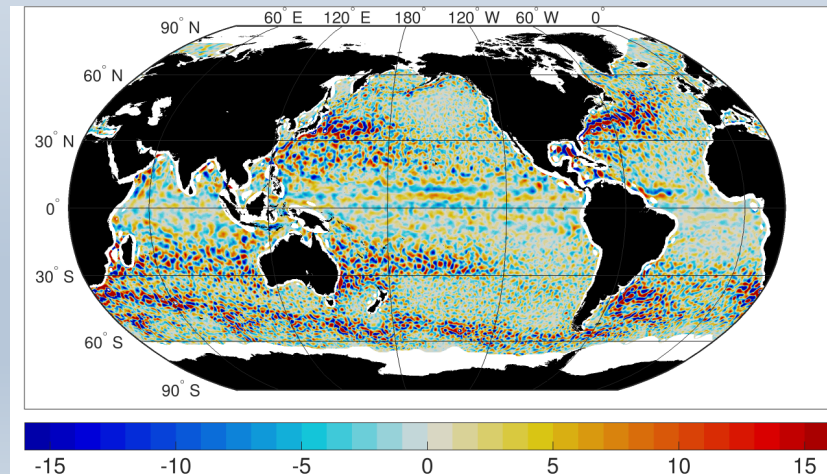
Mesoscale SSH$_{meso}$ (cm)

EKE impact on sea level variability due to anticyclonic/cyclonic bias?

- An anticyclonic or cyclonic bias at mesoscales appears to be responsible for the SSH-EKE relationship in many areas, most notably near strong currents.
    - Higher EKE + more **anticyclones** → **higher** sea level locally
    - Higher EKE + more **cyclones** → **lower** sea level locally
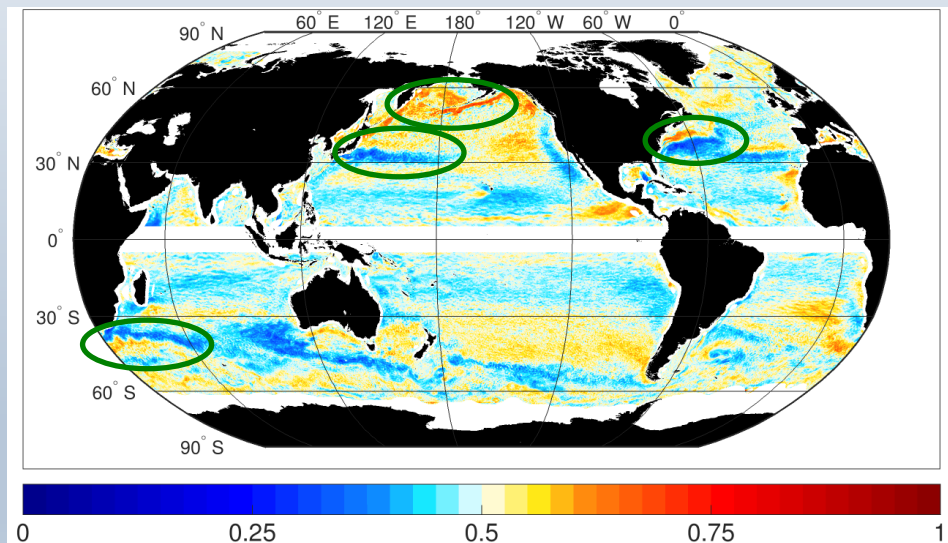
Fraction of EKE co-located with positive SLA_{meso}
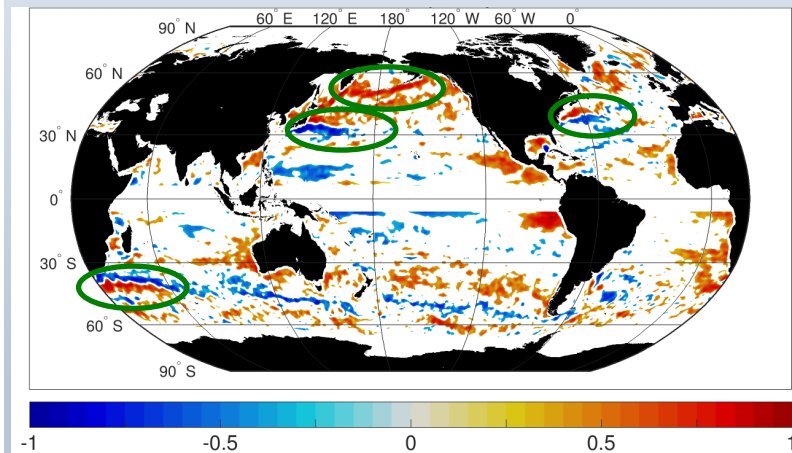
Local SSH-EKE correlation coefficient

Forcing of mesoscale variability by the atmosphere

- Surface winds (and planetary waves generated by them) may drive interannual/decadal variations in eddy generation, particularly near eastern boundaries
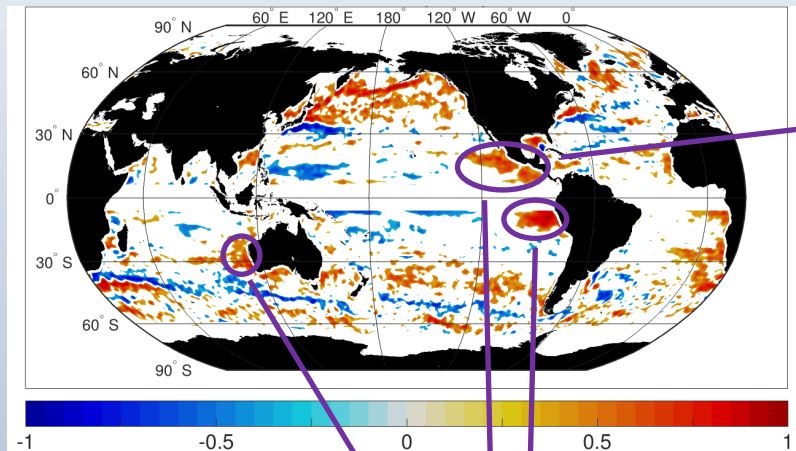
Local SSH-EKE correlation coefficient
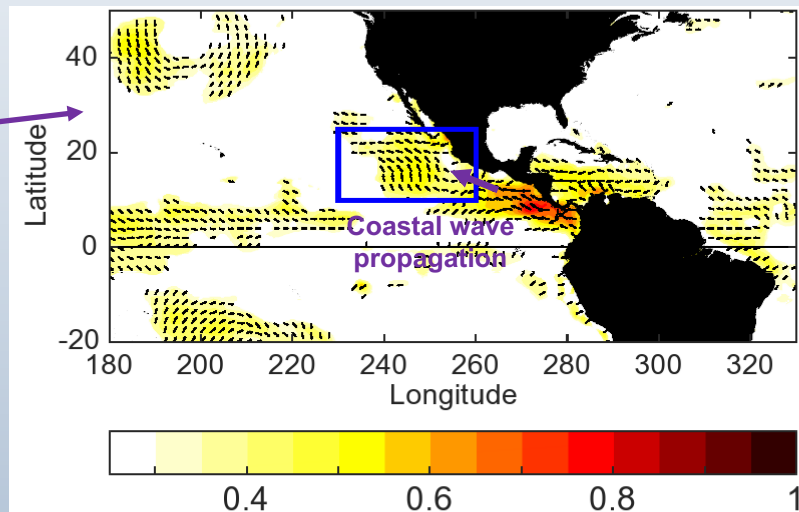
Box-averaged EKE correlated with CCMP 10 m wind:
Wind leads EKE by 6 months

- EKE variability in the lower-latitude Pacific and Indian Oceans is forced largely by wind and planetary waves associated with ENSO

Conclusions: Sea level and EKE co-variability

- Sea level and EKE co-vary on interannual and decadal timescales in many parts of the ocean; many of these regions fall into one of these categories:
 - **Proximity to strong energetic zonal currents:** when EKE is higher, meridional SSH gradient decreases (indicative of eddies mixing across the strong gradients)   **Mesoscale influences SSH**
  - **Tropical/subtropical ocean margins:** Planetary waves influence both SSH and EKE variability, often with a connection to a mode of large-scale climate variability   **Common forcing mechanism**

Local SSH-EKE correlation coefficient
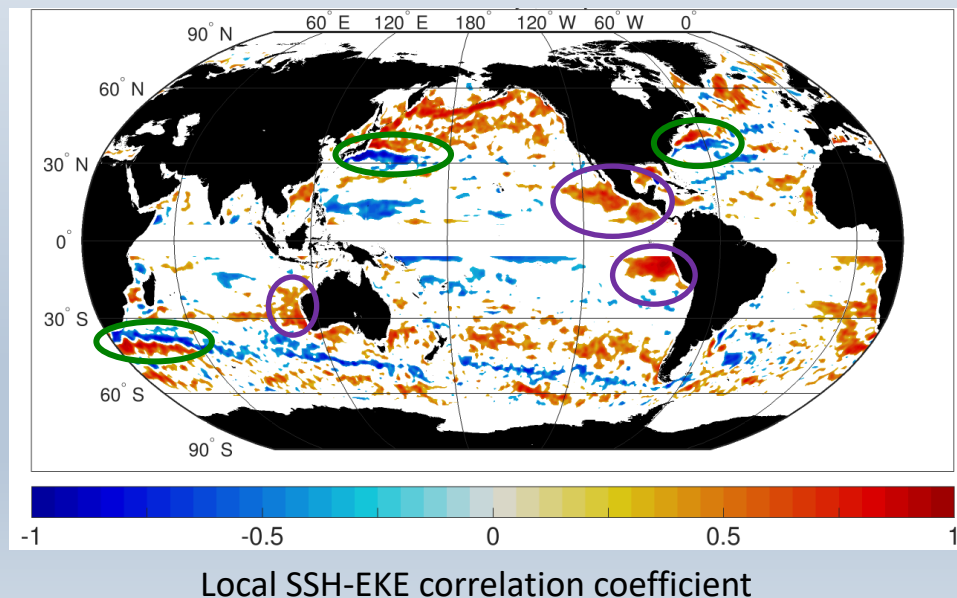
Part 2: What other characteristics of the ocean (that we can identify in observations and models/state estimates) contribute to interannual and decadal EKE variability?

Some motivation:

- Mesoscale eddy activity also varies on interannual/decadal timescales in ways that are not clearly forced by the large-scale climate
  - This is sometimes regarded as "internal" or "chaotic" variability

- Even EKE variability that may be related to large-scale climate (such as the possible influence of the Pacific Decadal Oscillation on the Kuroshio Extension) is **not well represented in ocean models**

Transition induced by PDO?

If so, then models should be able to simulate it…
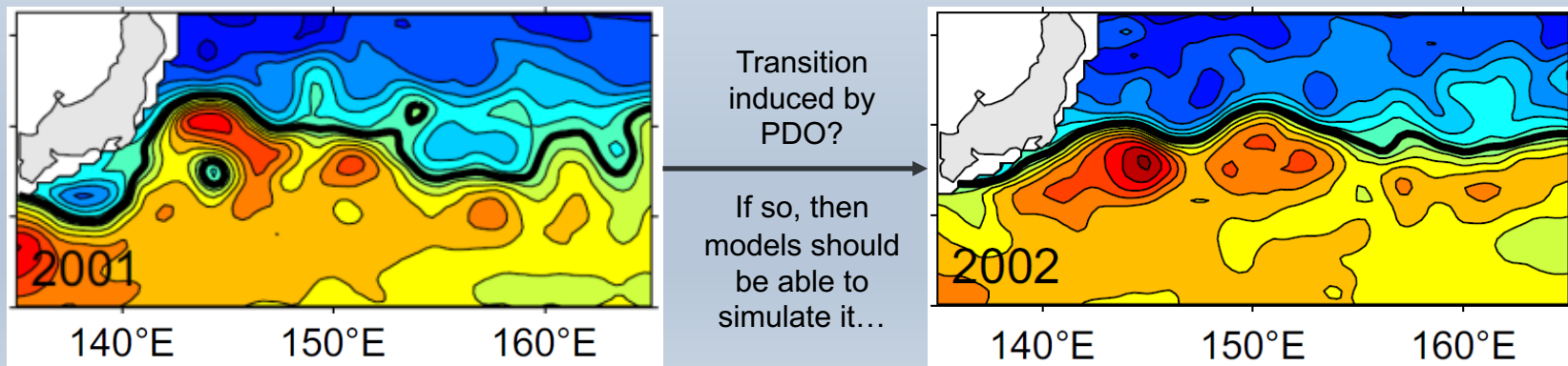
Qiu and Chen (2010)

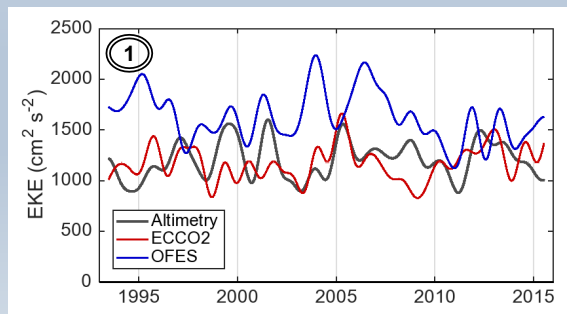# Challenge: Temporal variability of eddy kinetic energy (EKE) is generally not well represented in ocean models
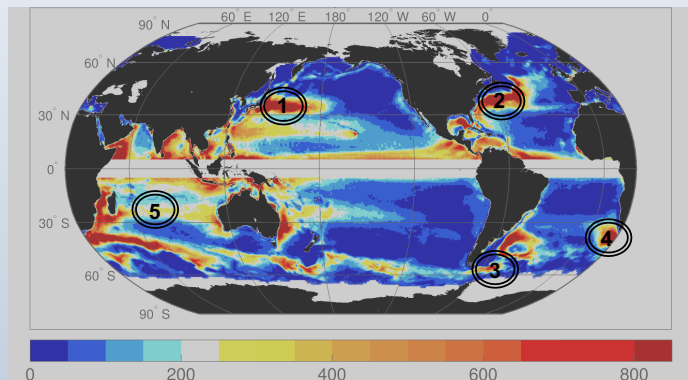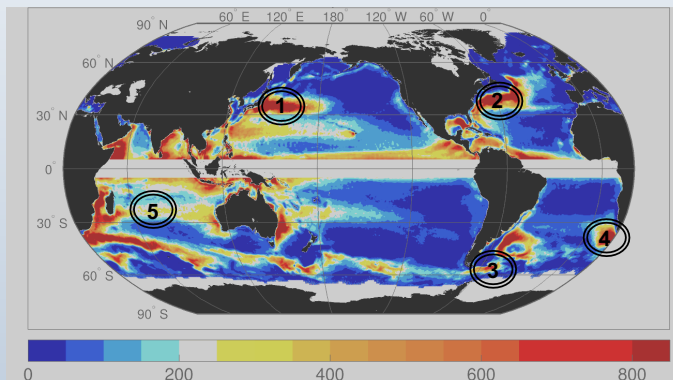
EKE time mean (cm^2 s^{-2})

Kuroshio Extension EKE

# Challenge: Temporal variability of eddy kinetic energy (EKE) is generally not well represented in ocean models

EKE time mean ($cm^2 \ s^{-2}$)

Surface EKE correlations of altimetry with models, 14-month low-passed

Altimetry correlation with…	ECCO2 18km Green's fcn. opt.	OFES 0.1° Forced, no assim.
Kuroshio Extension (1)	0.22	0.03
Gulf Stream Extension (2)	-0.03	0.10
Drake Passage outflow (3)	0.09	0.17
Agulhas rings (4)	-0.14	0.09
Southern central Indian Ocean (5)	**0.58**	**0.53**

Kuroshio Extension EKE
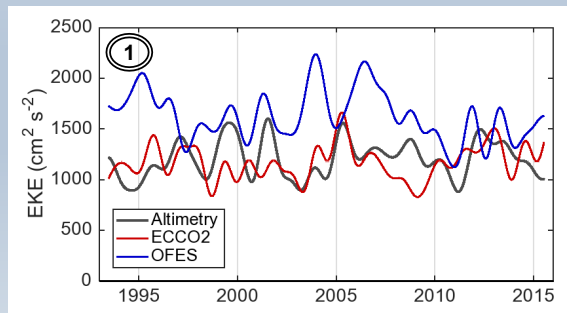
SC Indian Ocean EKE
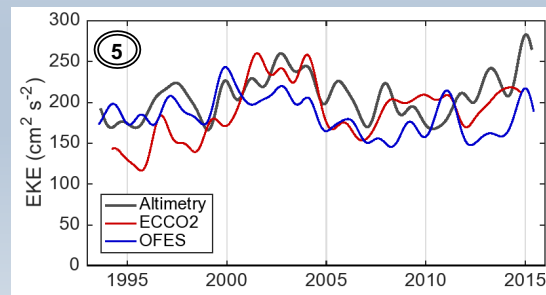
The impact of density gradients…on the mean state

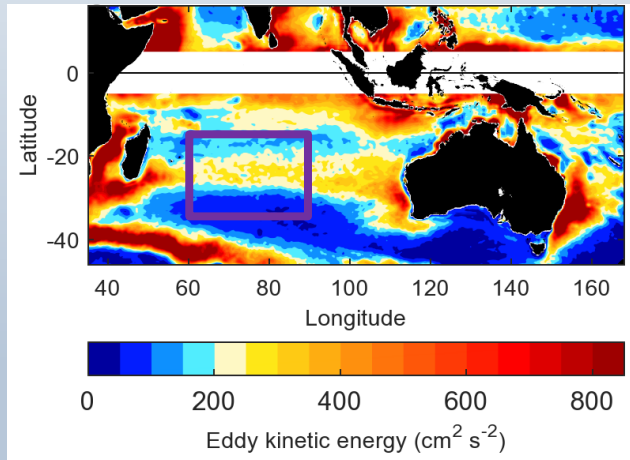- Available potential energy (APE) is a function of the local density variance at a given depth, related to the lateral density gradient $\nabla_H\rho$ (related to the "sloping" and "tightness" of isopycnals)
- We use output from the ECCO2 state estimate interpolated from the 18 km cube-sphere grid (Menemenlis et al., 2005) to examine these gradients

Time mean surface EKE from altimetry

Eddy band centered at ~25°S
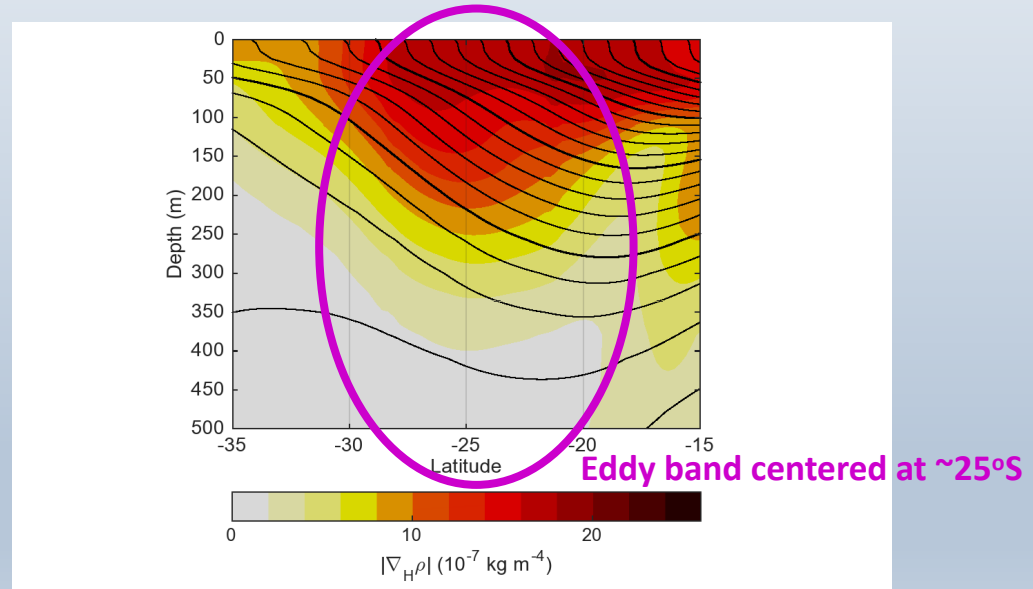
Magnitude of lateral density gradient from ECCO2
Time mean and zonally-averaged, south central IO

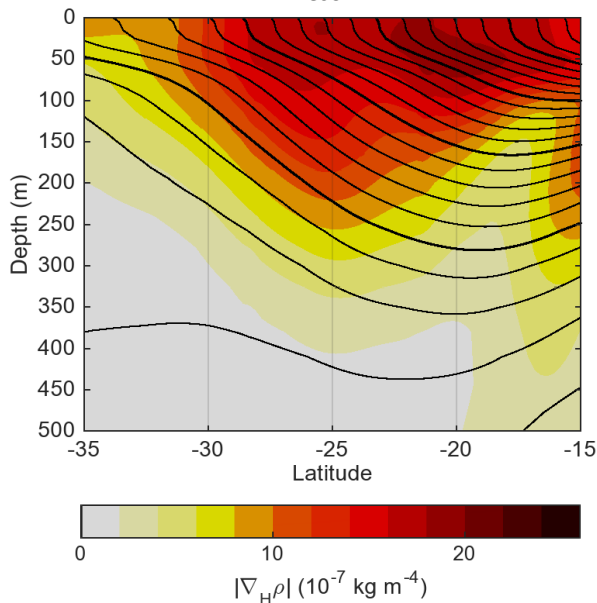**The impact of density gradients…on the interannual/decadal variability of eddies**

- **Lateral density gradients** help explain the existence of the eddy band…but do they explain its temporal variability?

High EKE$_{meso}$ composite | Low EKE$_{meso}$ composite | (High – Low) EKE$_{meso}$ difference

$|\nabla_H \rho|$ (10^{-7} kg m^{-4})

$|\nabla_H \rho|$ difference (10^{-7} kg m^{-4})
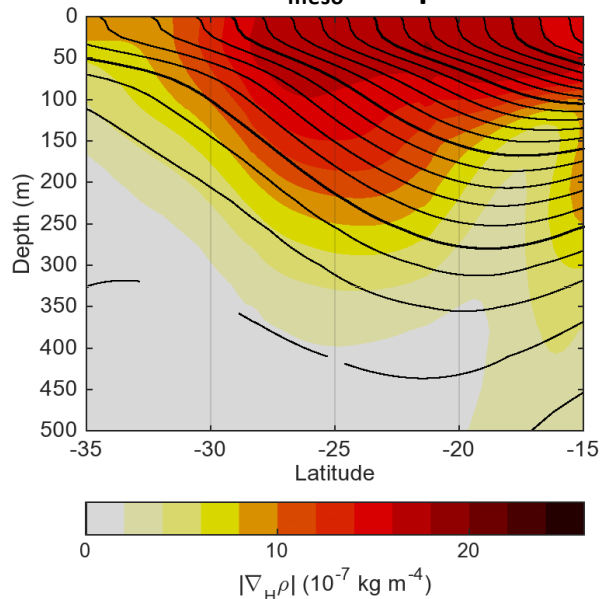
Statistically significant
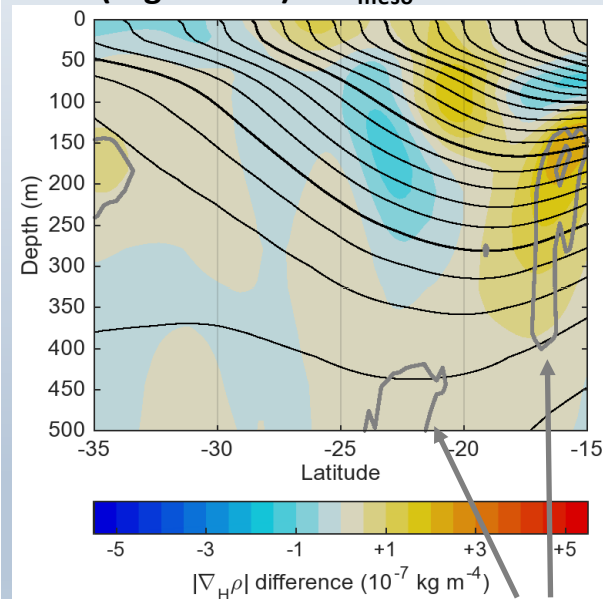
- Slight differences between composites of high vs. low eddy activity are generally **not statistically significant**

The impact of potential vorticity gradients
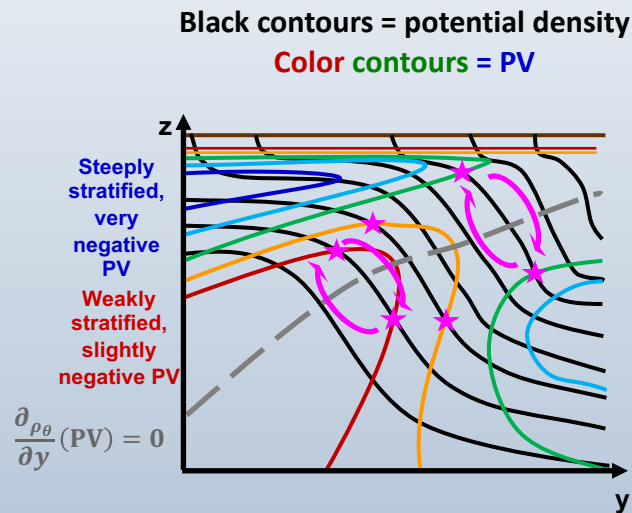
- Charney and Stern (1962) considered baroclinic instability (in the atmosphere) from the perspective of potential vorticity (PV) gradients along isopycnals

negligible in this region

$$PV = (f + \zeta)\left(-\frac{\partial \rho}{\partial z}\right)$$

Pos. in NH
Neg. in SH   Positive

Black contours = potential density
Color contours = PV

Steeply stratified, very negative PV

Weakly stratified, slightly negative PV
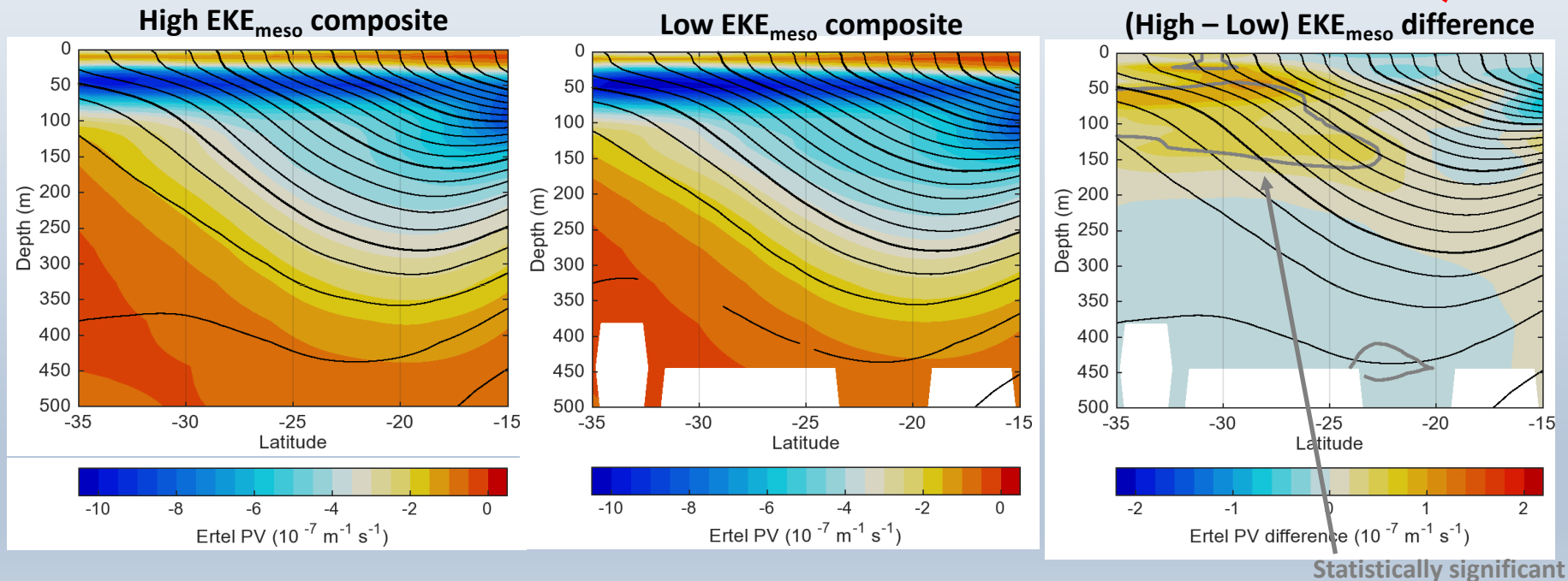
$$\frac{\partial_{\rho_\theta}}{\partial y}(PV) = 0$$

- **Zero crossing in the PV gradient** along a sloping isopycnal implies the potential for parcels at different depths but similar PV to be exchanged
  → potential release of APE and growth of baroclinic instability

The impact of potential vorticity gradients

- Is **potential vorticity** significantly different in the region during high vs. low eddy states?
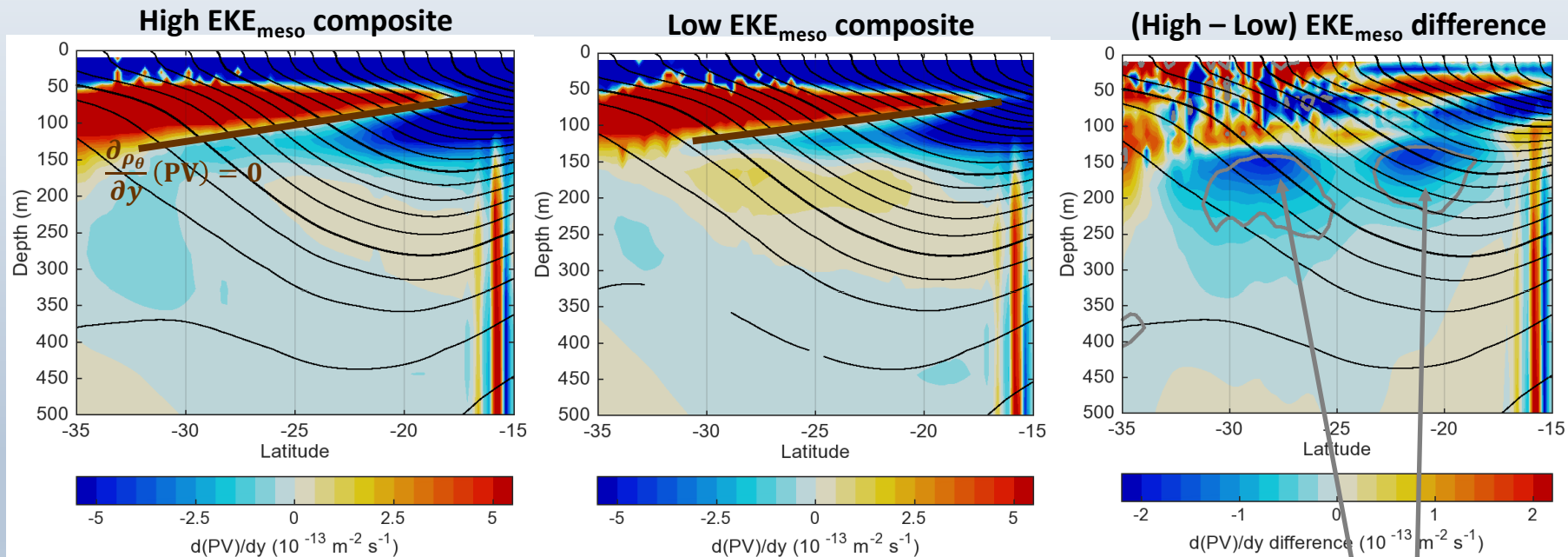
$$PV = (f + \zeta)\left(-\frac{\partial \rho}{\partial z}\right)$$

High EKE$_{meso}$ composite   **Low EKE$_{meso}$ composite**   **(High − Low) EKE$_{meso}$ difference**

Ertel PV (10^{-7} m^{-1} s^{-1})   Ertel PV (10^{-7} m^{-1} s^{-1})   Ertel PV difference (10^{-7} m^{-1} s^{-1})

Statistically significant

- Higher (more anticyclonic) PV in the southern part of the eddy band → more eddy activity

The impact of potential vorticity gradients

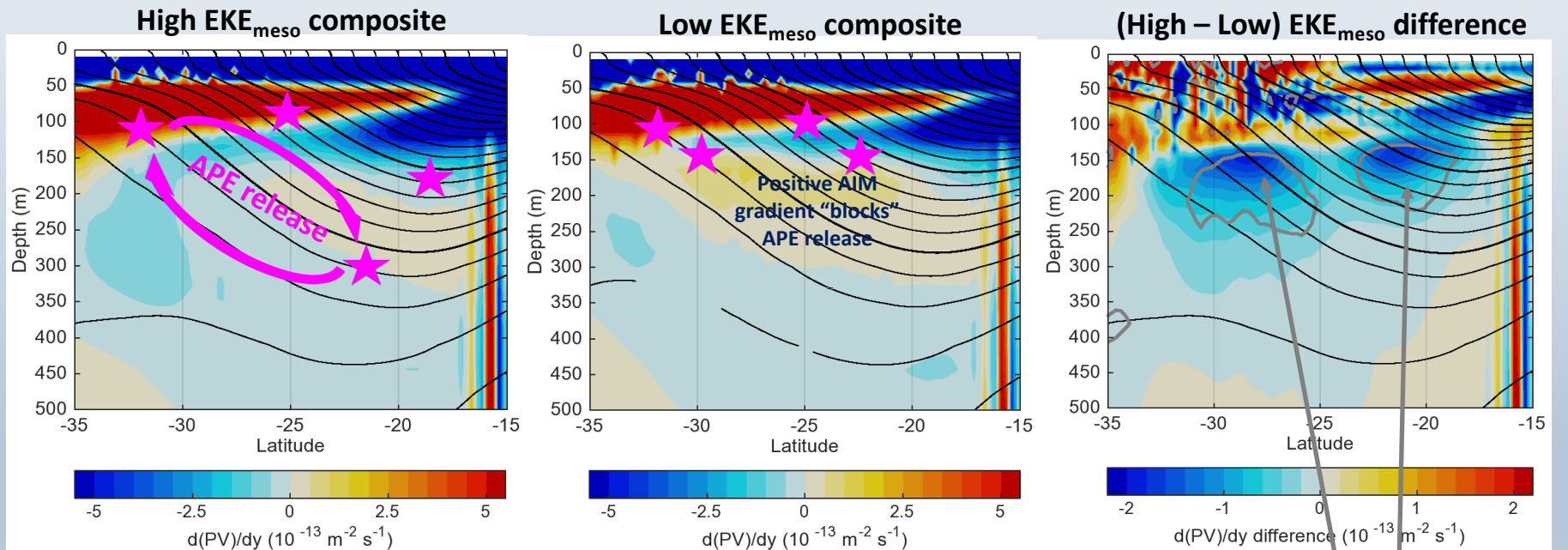- Now consider the **along-isopycnal meridional (AIM) gradient of potential vorticity**

High EKE$_{meso}$ composite   **Low EKE$_{meso}$ composite**   **(High – Low) EKE$_{meso}$ difference**

$$\frac{\partial \rho_\theta}{\partial y}(PV) = 0$$

d(PV)/dy (10^{-13} m^{-2} s^{-1})   d(PV)/dy (10^{-13} m^{-2} s^{-1})   d(PV)/dy difference (10^{-13} m^{-2} s^{-1})

Statistically significant

- There is a zero crossing during both states…but need sufficient negative gradient to balance the positive gradient

The impact of potential vorticity gradients

- Now consider the **along-isopycnal meridional (AIM) gradient of potential vorticity**

$$\frac{\partial_{\rho_\theta}}{\partial y}(\mathbf{PV}) = \mathbf{0}$$

High EKE$_{meso}$ composite   **Low EKE$_{meso}$ composite**   **(High – Low) EKE$_{meso}$ difference**

APE release

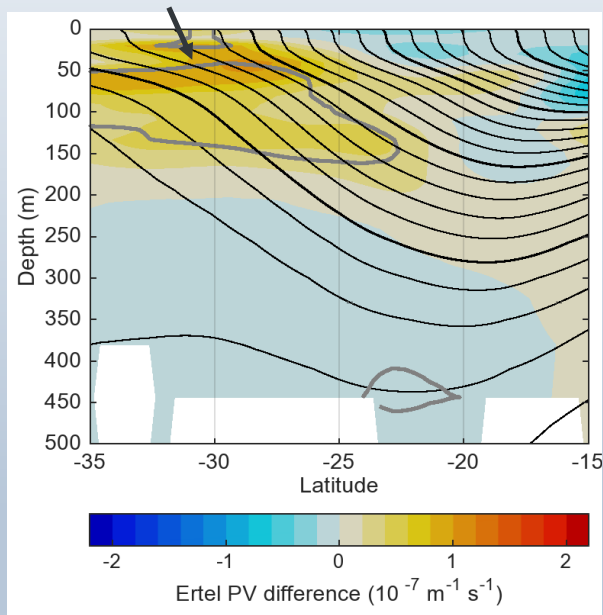Positive AIM gradient "blocks" APE release

Statistically significant

- This difference in states is likely a result of the positive PV anomaly on the southern side of the eddy band

If the PV anomaly influences mesoscale EKE levels, how is it forced?

Wind stress curl forces PV anomaly

(High − Low) EKE$_{meso}$ difference
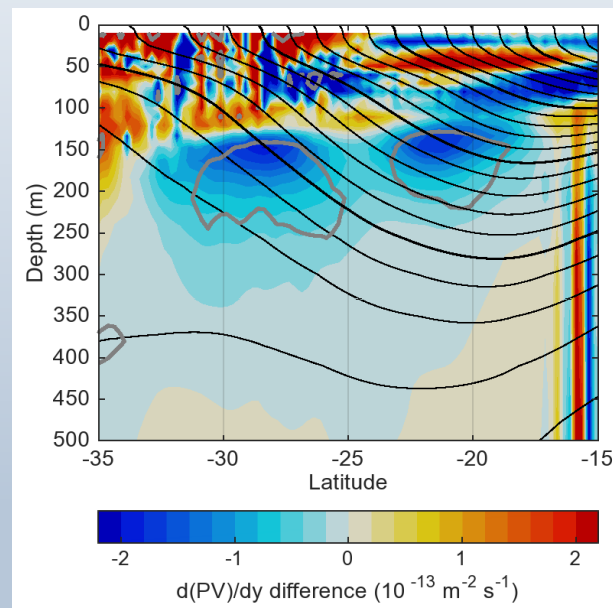
Delman et al. (2018)

- Downwelling (upwelling) wind stress curl may enhance (inhibit) eddy activity by forcing PV anomalies
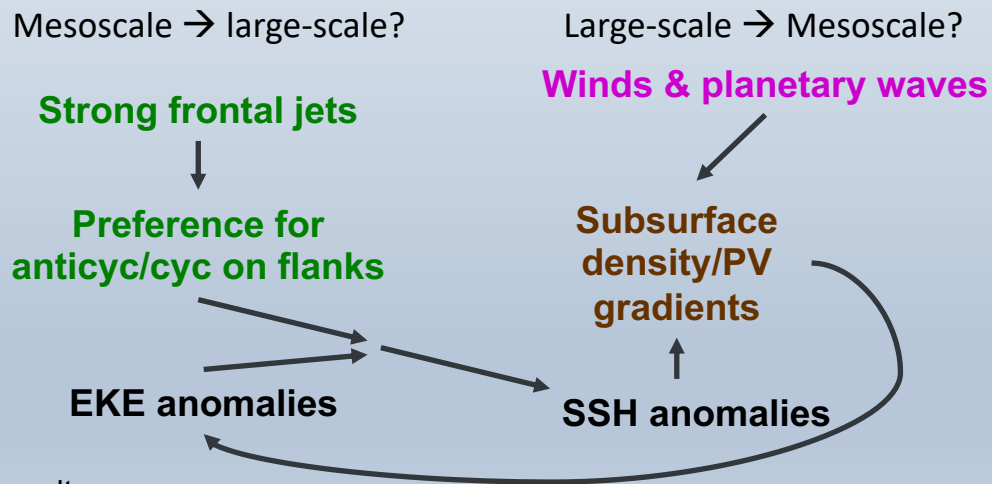
Conclusions

Part 1:
- Mesoscale eddies generated near strong currents contribute to sea level variability on the flanks of the current
- Large-scale climate variability contributes to EKE variability, especially in tropics/subtropics

Part 2:
- Considering density and PV gradients may help us understand what drives eddy variability in the real ocean, and ultimately improve its representation in models

Mesoscale → large-scale?   Large-scale → Mesoscale?

Winds & planetary waves

Strong frontal jets

Preference for anticyc/cyc on flanks

Subsurface density/PV gradients

EKE anomalies   **SSH anomalies**

- For more detailed insight into these mechanisms consult:
  Delman, A. S., Lee, T., & Qiu, B. (2018). Interannual to multidecadal forcing of mesoscale eddy kinetic energy in the subtropical southern Indian Ocean. *J. Geophys. Res. Oceans*, 123. https://doi.org/10.1029/2018JC013945.

Upcoming work – more impacts of mesoscale on climate variability and ocean mixing
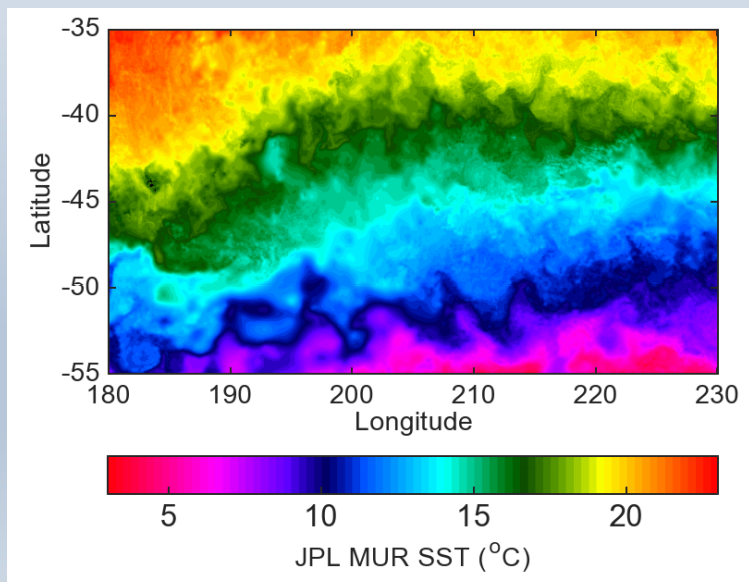
- Characterize the specific contributions of mesoscale dynamics to meridional heat/freshwater transports and mixed layer budgets

- Use JPL Multi-Scale Ultra-high Resolution (MUR) SST to help estimate lateral diffusivity associated with mesoscale mixing

- Investigate the impact of mesoscale asymmetry on all of the above

Eddy meridional heat transport variance, as % of total
(Volkov et al. 2008)
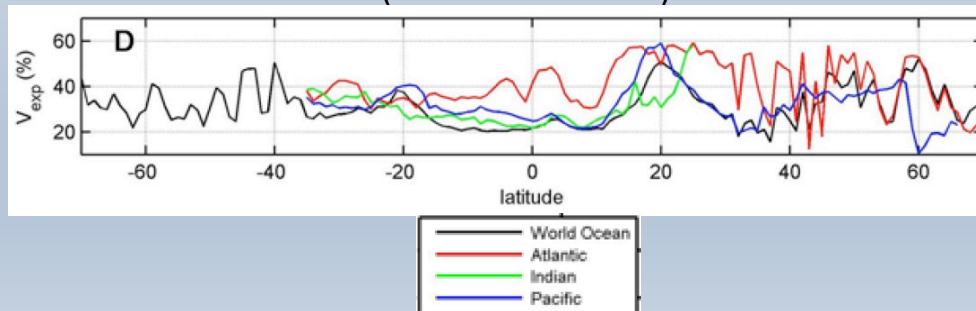
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MUR SST snapshot, South Pacific
2018 Feb 01

Upcoming work – more impacts of mesoscale on climate variability and ocean mixing

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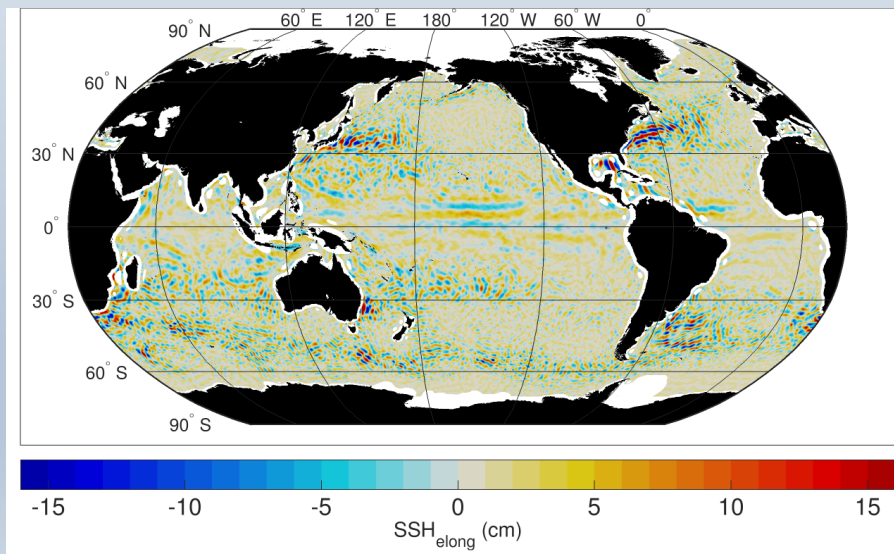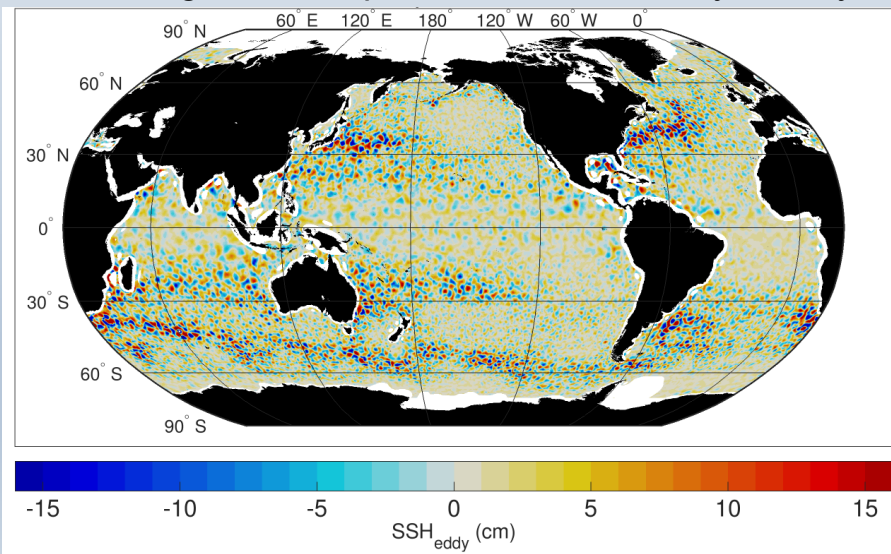
Decomposition of mesoscale SSH field into symmetric (eddy) and asymmetric (elongated) components, 1998 Jan 01
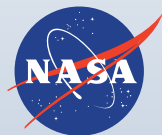
Jet Propulsion Laboratory
California Institute of Technology

jpl.nasa.gov

SSH gradient and EKE co-variations

- At the surface $\text{EKE} \propto |\nabla \text{SSH}|^2$, so we expect that the $|\nabla \text{SSH}|$-EKE correlation will be positive by definition
  - It is in most places, but if the correlation is computed with most mesoscale variations removed, the correlation turns negative along strong currents
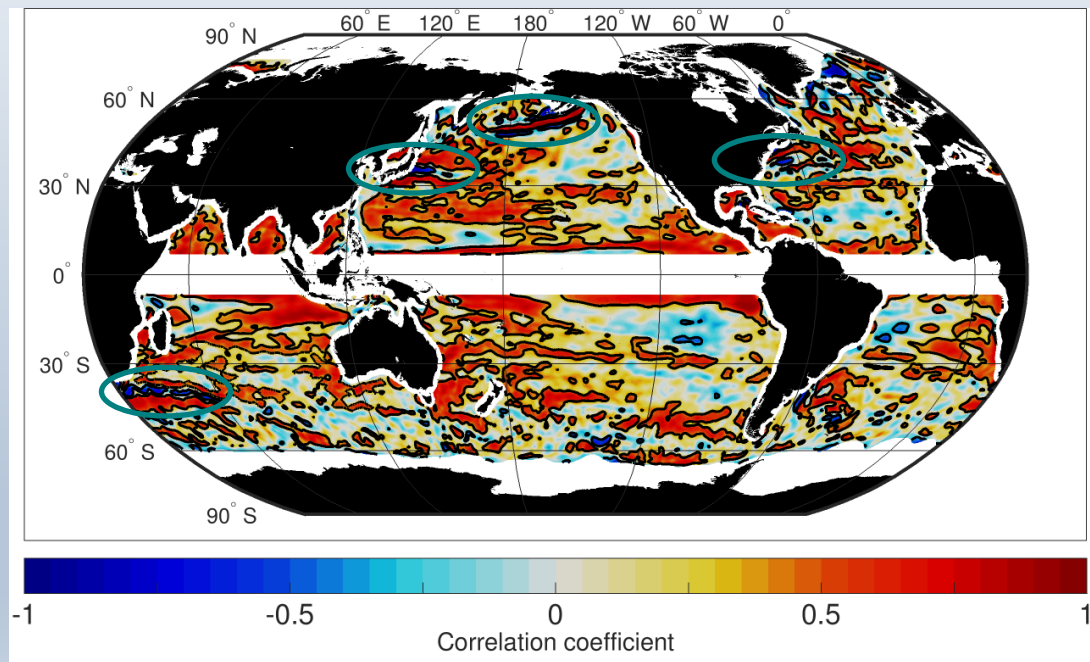

Local correlation of SSH gradient and EKE, smoothed with Gaussian filter (2° e-folding radius)
(contours indicate 95% significance level)

Eddy ratio (Chelton et al. 2011)
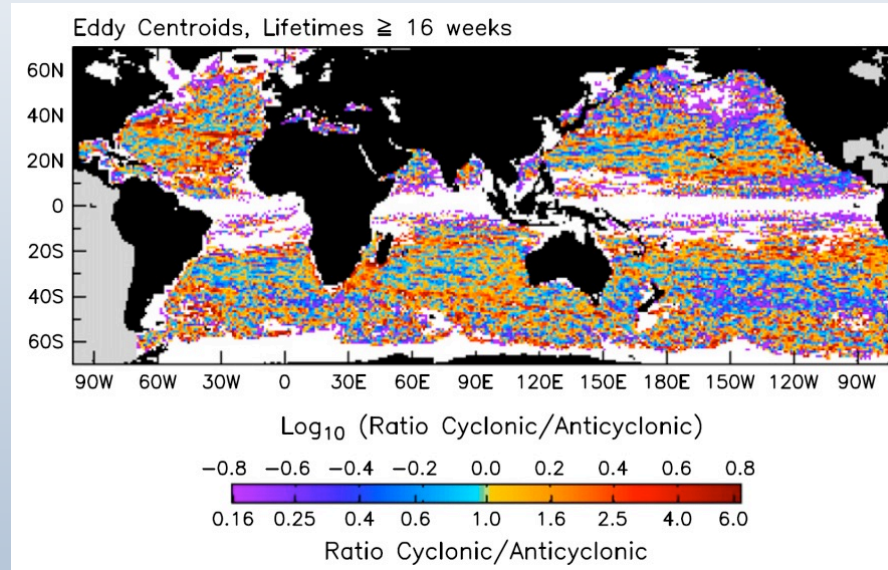
## Pacific influences eddy activity in the eastern SSIO

- In short, we have a robust (if somewhat complicated) explanation for the influence of Pacific sea level and climate forcing on eddy activity in the **eastern SSIO**
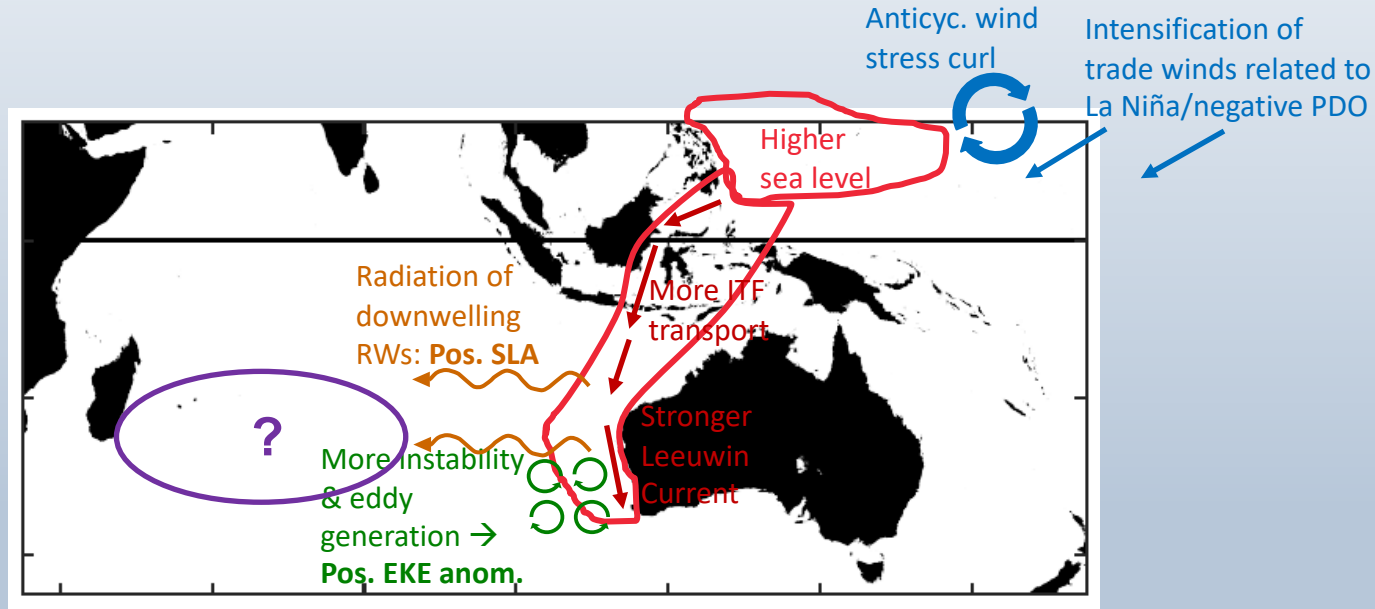
- However, Pacific forcing does not explain mesoscale EKE variability in the **central and western SSIO**

- What drives eddy variability away from the Leeuwin Current (central & western SSIO), in the absence of forcing from the Pacific?

Hovmöller diagram of mesoscale EKE,
averaged 25°-20° S
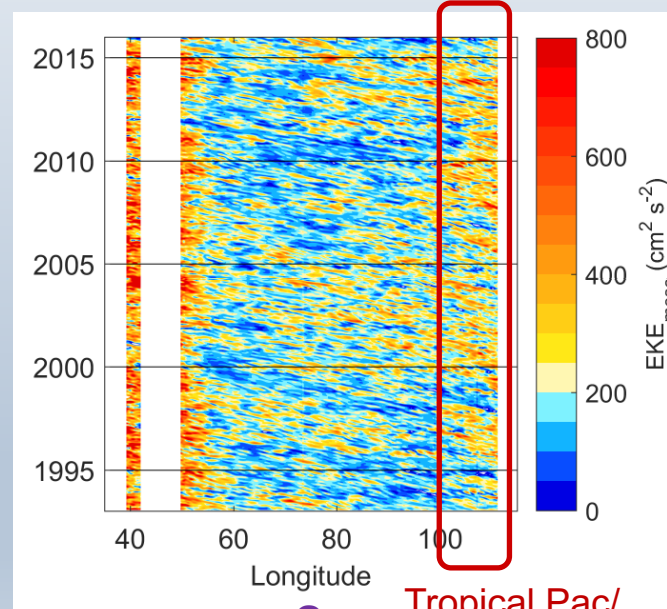
?   Tropical Pac/ ENSO-driven

The impact of density and potential vorticity gradients

- Charney and Stern (1962) considered baroclinic instability (in the atmosphere) from the perspective of potential vorticity (PV) gradients along isopycnals

negligible in SSIO

$$PV = (f + \zeta)\left(-\frac{\partial \rho}{\partial z}\right)$$
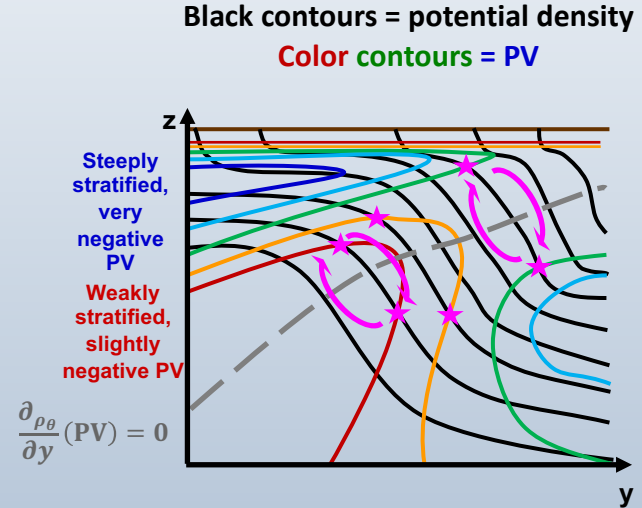
Pos. in NH
Neg. in SH   Positive

Black contours = potential density
Color contours = PV

z

Steeply stratified, very negative PV

Weakly stratified, slightly negative PV

$\frac{\partial_{\rho_\theta}}{\partial y}(\text{PV}) = 0$

y

- Zero crossing in the PV gradient along a sloping isopycnal implies the potential for parcels at different depths but similar PV to be exchanged
  → potential release of APE and growth of baroclinic instability

If the PV anomaly influences mesoscale EKE levels, how is it forced?

**Correlation of wind stress curl (from CCMP), leading box-averaged EKE$_{meso}$ by 6 months**
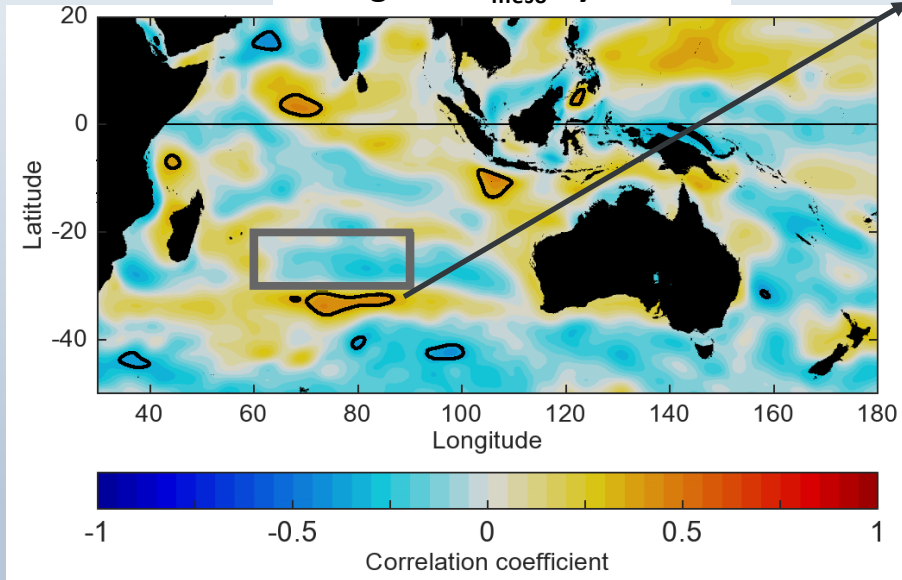
Wind stress curl forces PV anomaly
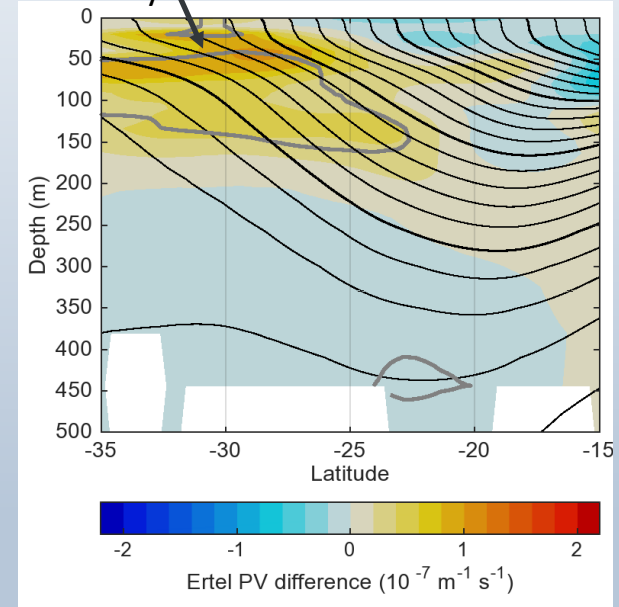
- Hence we have one mechanism for forcing of eddy activity in the west central SSIO
  - Downwelling (upwelling) wind stress curl enhances (inhibits) eddy activity by forcing PV anomalies

Global implications: the relationship between sea level and EKE
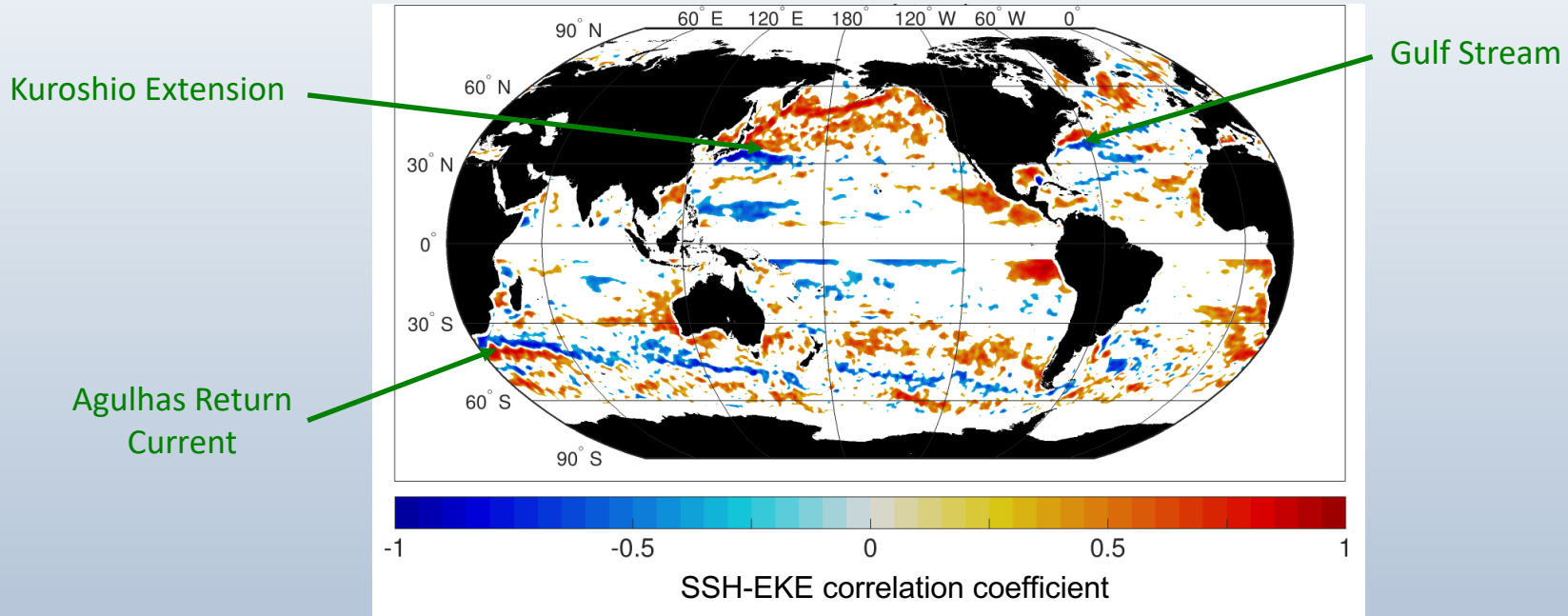
- The temporal variability of EKE is associated with sea level in a number of regions

- Some of these areas have energetic currents and very high levels of eddy activity
    - Often there is a preference for cyclonic (anticyclonic) eddies on the equatorward (poleward) side of strong currents → sea level impact

Global implications: the relationship between sea level and EKE

- The sea level-EKE relationship at interannual/decadal timescales may also have implications for multi-decadal trends

+ SSH-EKE corr. & + EKE trend → increased SSH trend?
     N & S Pacific, S Indian
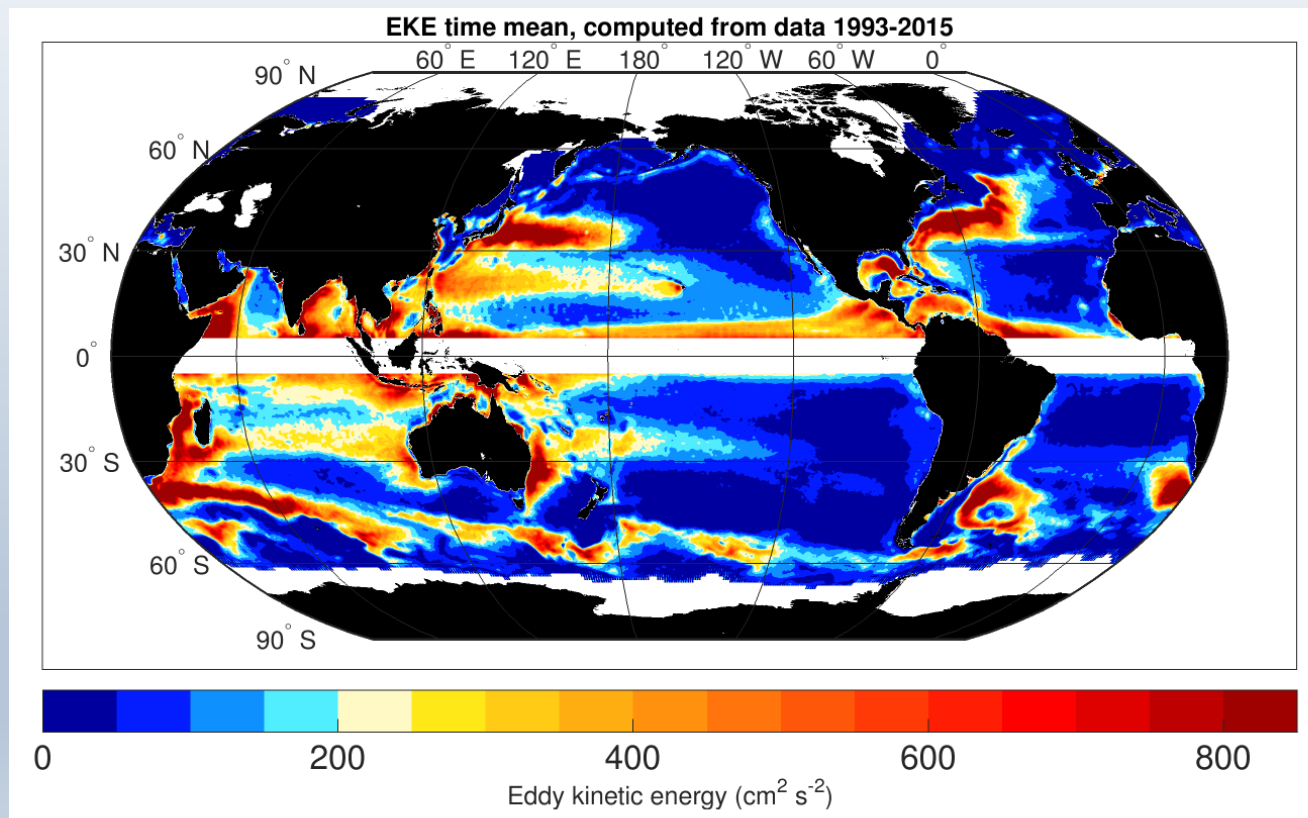**+ SSH-EKE corr. & - EKE trend → decreased SSH trend?**
     N Atlantic
 - SSH-EKE corr. & + EKE trend → decreased SSH trend?
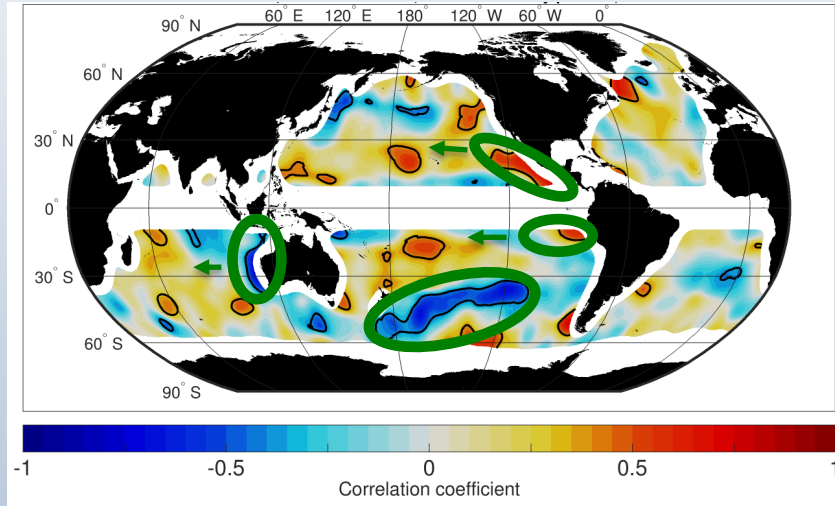   S Pacific (just north of the Polar Front)

SSH-EKE correlation coefficient

EKE trend (% yr^{-1}), 1993-2016

SSH trend minus global mean (cm yr^{-1}), 1993-2016

EKE time mean

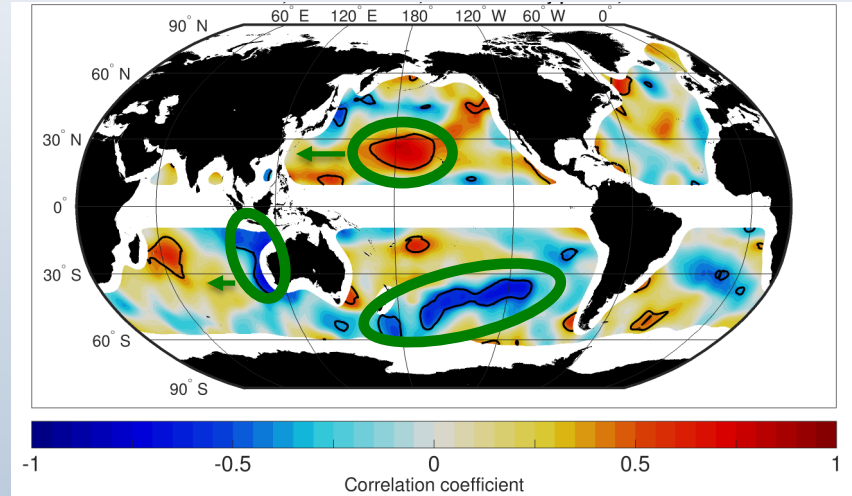EKE time mean, computed from data 1993-2015
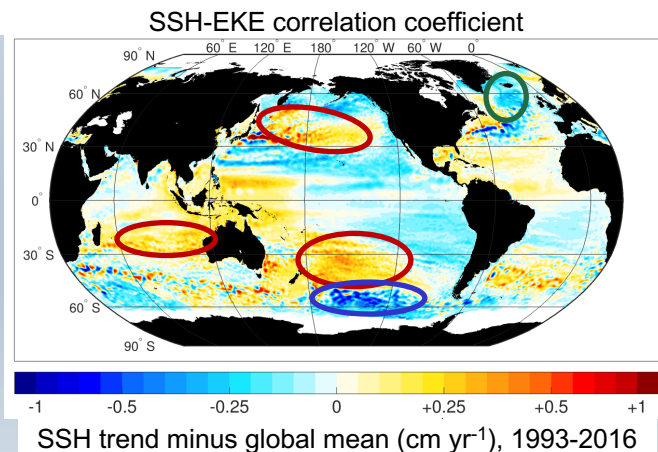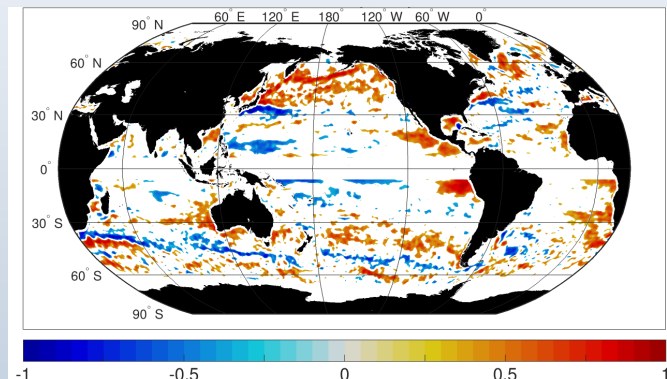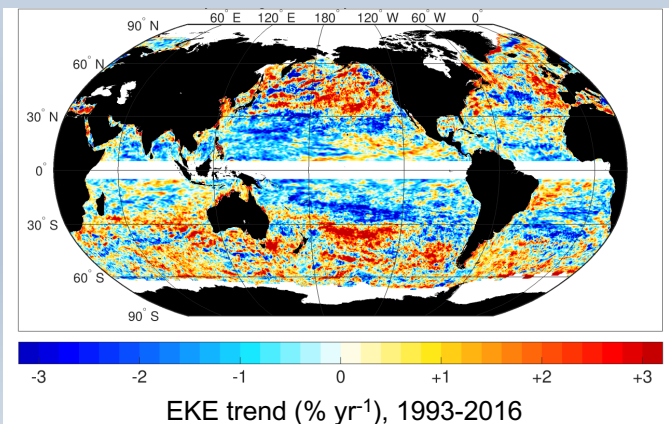
Forcing of EKE interannual/decadal variability globally

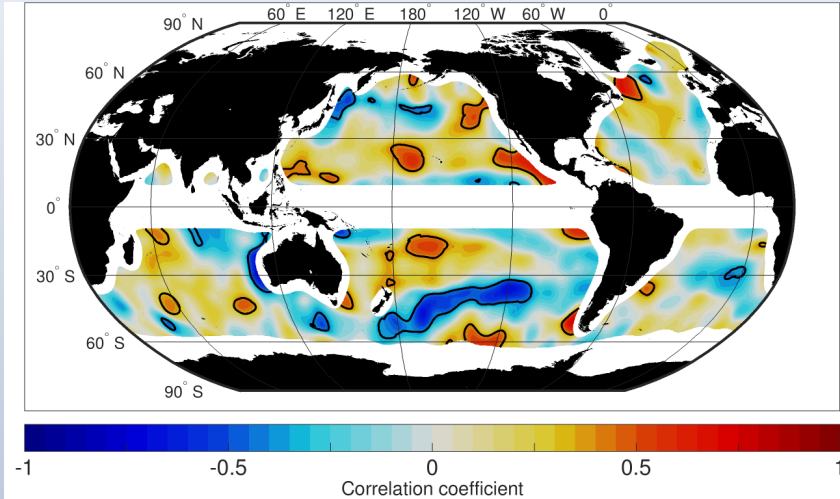Niño3.4-EKE correlation
0 lag

PDO-EKE correlation
0 lag

- Effect of the Pacific Decadal Oscillation (PDO) on EKE is similar to the effect of ENSO…
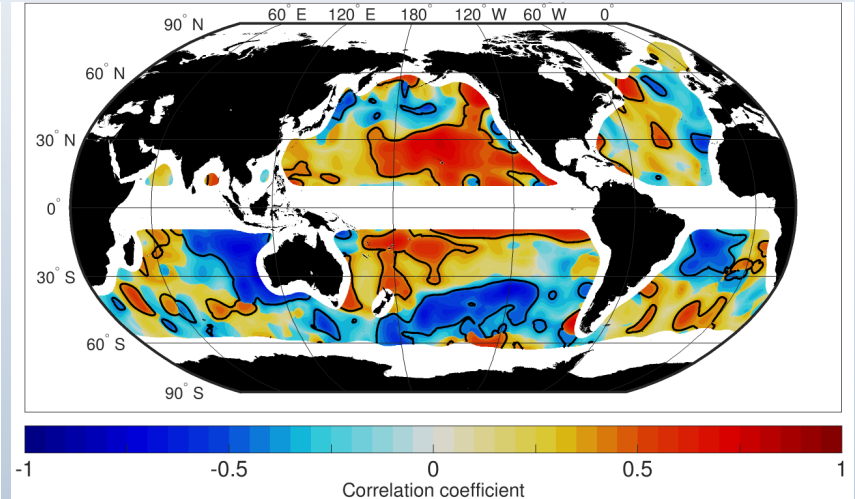 but more focused on the interior of the ocean

Forcing of EKE interannual variability globally

Niño3.4-EKE interannual/decadal correlation
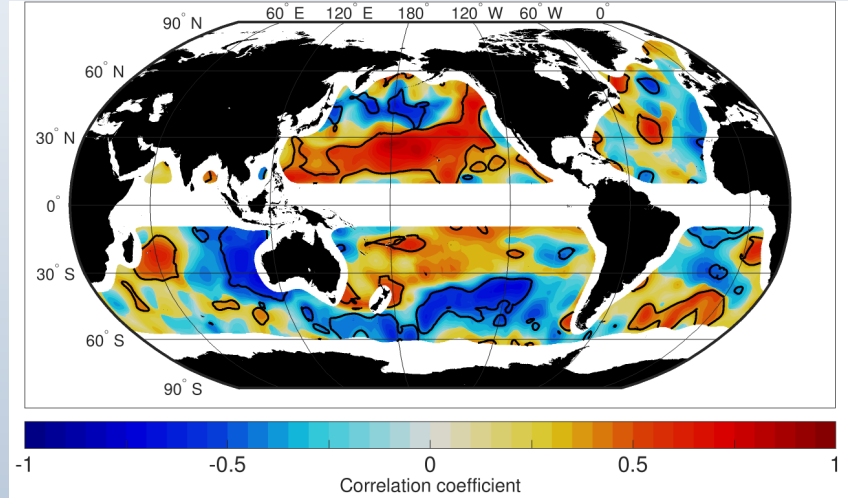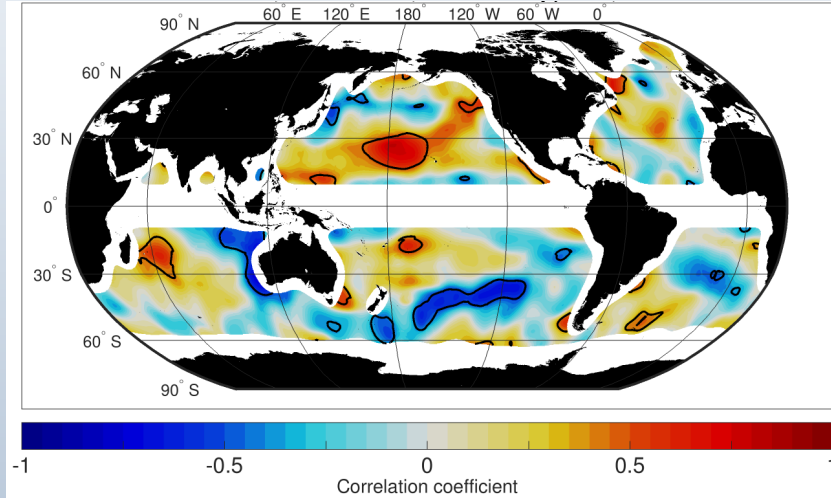

0 lag

Optimum values: ENSO leads EKE by 0-2 years

Forcing of EKE interannual variability globally
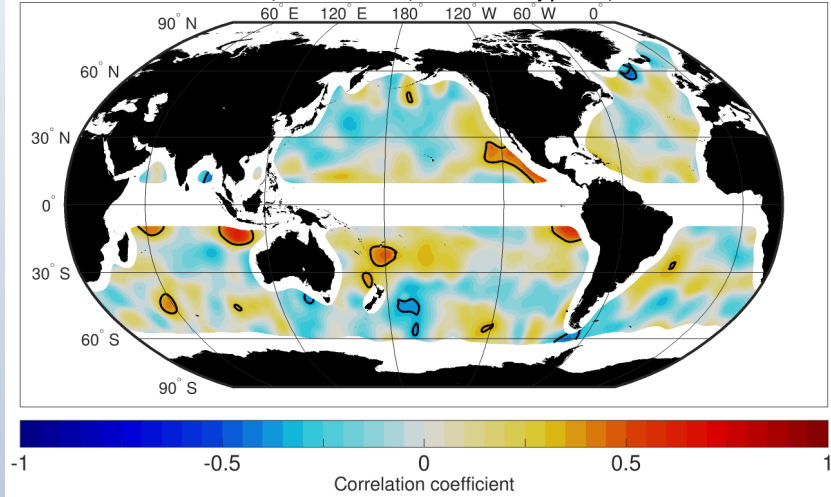
PDO-EKE interannual/decadal correlation
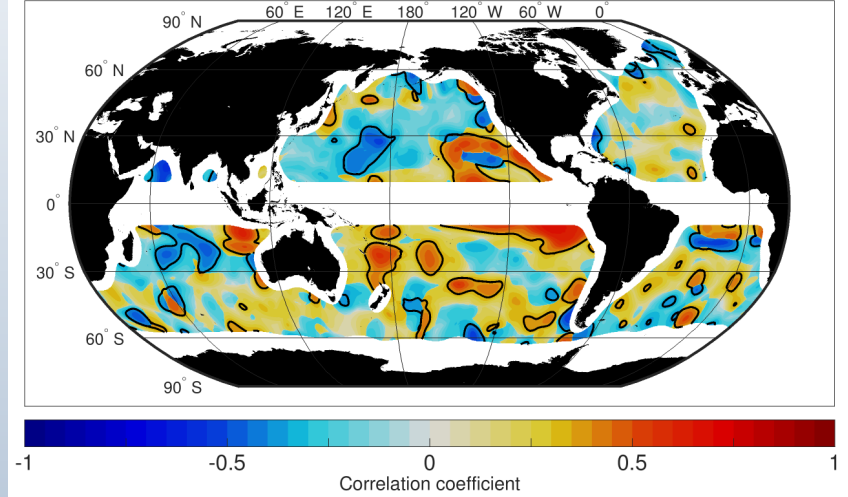
0 lag

Optimum values: PDO leads EKE by 0-2 years

Forcing of EKE interannual variability globally

IOD-EKE interannual/decadal correlation

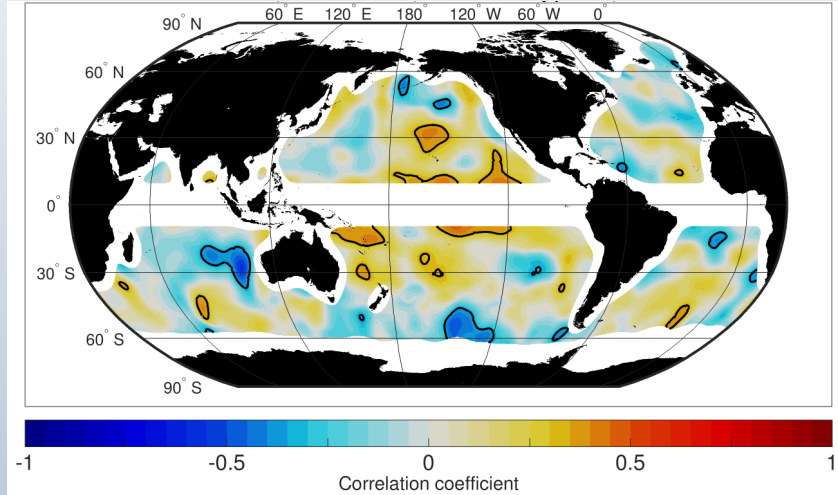# Forcing of EKE interannual variability globally

SAM-EKE interannual/decadal correlation

0 lag

Optimum values: SAM leads EKE by 0-2 years